# STUDY OF TRANSISTOR LINEAR AND SWITCHING VOLTAGE REGULATORS FOR USE IN POWER CONDITIONING

By

Thomas Joseph Solak

# United States Naval Postgraduate School

# THESIS

STUDY OF TRANSISTOR LINEAR AND SWITCHING VOLTAGE REGULATORS FOR USE IN POWER CONDITIONING

by

Thomas Joseph Solak

December 1970

# Study of Transistor Linear and Switching Voltage Regulators for Use in Power Conditioning

by

Thomas Joseph Solak
Major, United States Marine Corps
B.S., United States Naval Academy, 1960

Submitted in partial fulfillment of the
requirements for the degree of

MASTER OF SCIENCE IN ENGINEERING ELECTRONICS

from the

NAVAL POSTGRADUATE SCHOOL
December 1970

## ABSTRACT

A requirement exists for a portable direct energy source 60 watt power supply with adjustable output voltage between 24 and 28 volts. Integrated circuit and discrete transistor linear and switching voltage regulators with these outputs were designed, breadboarded and tested with intent toward use in such power supplies. A summary of design characteristics of the transistors and circuits is given, while the resulting test data is presented in tabular and graphical form. A feasibility study of using the tested regulators in conjunction with a dc-dc converter to form a power conditioner is also presented.

TABLE OF CONTENTS

## LIST OF TABLES

## LIST OF FIGURES

## ACKNOWLEDGEMENT

The author expresses his sincere appreciation for the scholarly advice and willing assistance given by Professors W. M. Bauer and R. P. Murray in the development of this thesis.

# I. INTRODUCTION

During the past decade, solid state electronics, with the advent of metallic oxide semiconductor (MOS) techniques and the microminiaturization of large scale integration (LSI), has enabled such rapid progress in equipment development that the military is wanting for power sources which are compatible. These new electronics end-items which will be replacing present tube, solid state and combination tube/solid state devices will be "... smaller in size, require lower power and, what is most important, will offer an extremely long operating life with ultra-high reliability..." [3]. Engineers are speaking in terms of 6,000 to 10,000 hours Mean Time Before Failure (MTBF) of "... suitcase size digital processors..." [3]: the military possesses batteries and multi-thousand/several-hundred pound hydrocarbon powered internal combustion generators to drive these new devices. A difficult situation, at best, especially when one realizes that much of what a Marine/soldier will use in the field must be carried on his back. Then, considering smallness, only the batteries are compatible; yet there have been no "... recent major breakthroughs in the state-of-the-art batteries..." [19]. Manufacturers continue to seek new horizons which will increase the reliability, capacity and cycle life/lifetime of batteries, but battery power densities remain small. To date, only 20 to 40 watt-hours per pound can be obtained from batteries, whereas, if properly utilized, a chemical such as lithium hydride can give up to one kilowatt-hour of electrical power per pound [5] and solid state semiconductors can provide, for example, 200 watt-hours per pound of fuel [1].

In an attempt to utilize this energy, the U. S. Army Electronics Command (USAECOM) has directed the study and development of thermoelectric generators and fuel cells with greater capacity and more reliability than batteries for manpack use. Presently, most of the manpack power sources are general utility types designed for a broad range of applications. It would be easier to develop special purpose sources, i.e., ones that would drive particular pieces of communications or surveillance equipment, or ones that would charge batteries. The battery chargers must have variable output voltages to match any of the variety of battery types in existence while output ripple or electrical noise are of little consequence. On the other hand, the power source for a single communication device requires one precise voltage; but no output ripple or radio frequency interference [2]. Despite these conflicts, the military needs a general utility power source to absorb the battery's ease of installation, ease and silence of operation, immediate, continuous power, and multi-end item compatibility, i.e., one battery with multi-socket outputs can service any one of several devices. Also, an operator of a field radio "...has more important things to do than read dials and gages, and twist knobs on the power source..." [2]: and, many times a critical situation requires that an untrained man get reliable communications. The power source, then, must be fully automatic in its operation "...adjusting the fuel-feed rate to match any arbitrarily selected load..." [2].

There exists a specific Marine Corps requirement [18] to convert a dc output of a cell/generator at 6-10 volts, 80 watts to an adjustable 24-28 volts, 60 watts input to portable systems. The cell/generator voltage varies within the stated range depending on fuels used and

ambient temperature. Useful loads require 45 watts, while 15 watts is allocated to cell/generator control. Other design considerations are low weight and voltage regulation of 0.05% from half load to full load. A block diagram expressing this design is shown in Fig. 1. Application of this power conditioned source will be found in use with battlefield radar sets, beacon systems and communications used by perimeter defense teams, forward observers and reconnaissance teams.

As a preliminary study toward eventual development of the power conditioner, this paper will investigate the feasibility of a dc-dc converter/voltage regulator design, similar to that shown in Fig. 2, by analysis of linear and switching voltage regulators and mathematical computation of efficiencies involved. The term, power conditioner, as used herein, means an electronic circuit assembly which processes electrical power available in an unusable state, with regard to voltage, current and degree of regulation, to electrical power in a usable state having appropriate characteristics. The specific case referred to is that of converting the low voltage, high current, poorly regulated dc power produced by a direct energy source, such as a fuel cell or thermoelectric generator, to usable dc power. This conditioner is considered to contain a power converter with the necessary auxiliary circuitry to provide the required output.

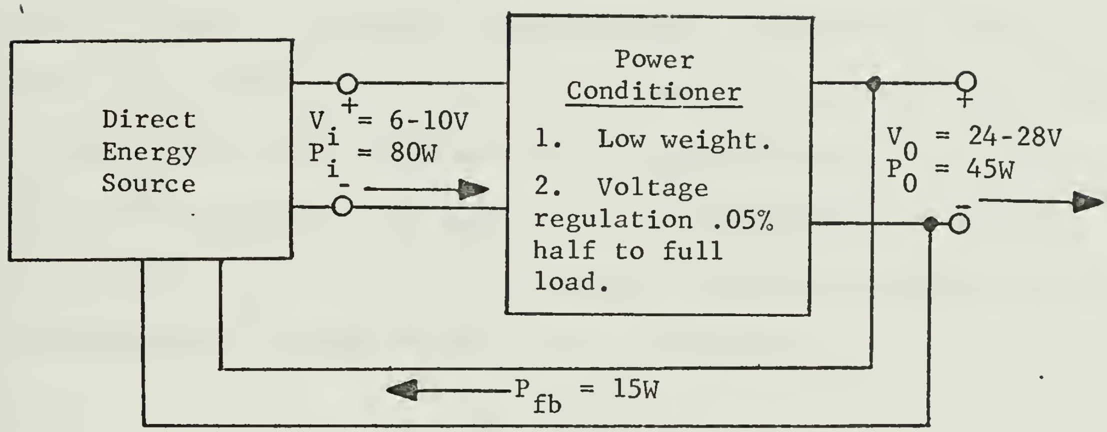



Fig. 1. Power Source Concept

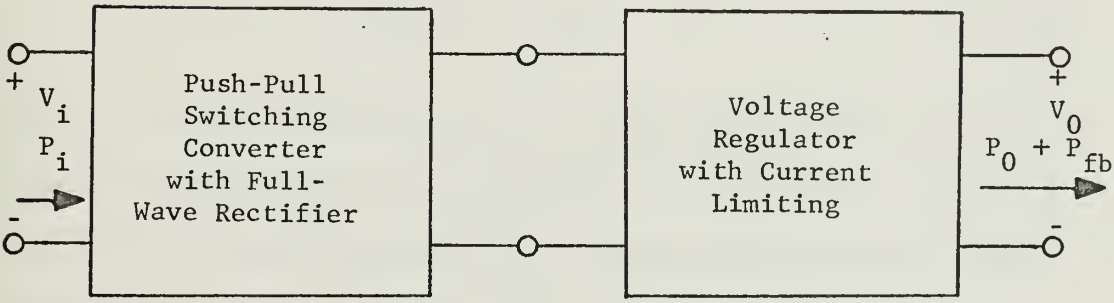



Fig. 2. Power Conditioner

## II. VOLTAGE REGULATORS - GENERAL

It has long been known that the circuitry of audio and video amplifiers produces a properly amplified signal with little or no distortion if the dc bias of the active devices is correct. To get this bias, what one might desire or think to be an ideal voltage source, i.e., a constant voltage under all load conditions, is not practically available. A practical voltage source is represented by an ideal voltage source in series with an internal resistance, as shown in Fig. 3.

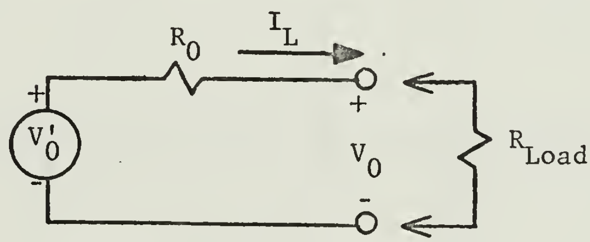



Fig. 3. Practical Voltage Source.

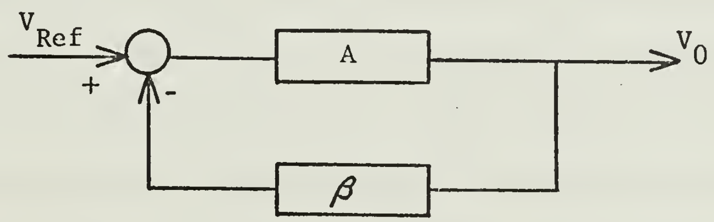
It can be seen then that the output voltage is dependent upon the load current by the relation

$$V_0 = V_0' - I_L R_0 . \qquad (2\text{-}1)$$

If $R_0$ is not small compared to $R_{Load}$ the output voltage can vary considerably with load and can subject the dependent amplifiers to inadvertent nonlinear distortion and regenerative feedback [17]. Regenerative feedback of this type is uncontrolled feedback from output to input which might cause unwanted oscillations. It is more likely to occur the higher the gain of the amplifier and the higher the internal impedance of the power source. Since the power source biases all active devices from input to output, it works through its

internal impedance, in consonance with the high gain, to increase the amount of destructive voltage feedback. Good voltage regulators have low internal impedance at low frequencies and can, therefore, be an asset in eliminating regeneration, tending to make the destructive feedback negligible.

Such voltage regulators are usually feedback control devices which sense the change in output voltage, compare this change to a reference voltage and amplify the error signal generated, thereby tending to cancel the output voltage change.




$$V_0/V_{Ref} = A/(1 + A\beta) \tag{2-2}$$

Their performance is often specified by means of the following parameters:

1. Output impedance, $\Delta V_0 / \Delta I_0$, over a wideband of frequencies, particularly at low frequencies. As has been noted above, the output impedance of the regulator must be small especially at low frequencies. Typical values are 0.1 ohm below 2KHz and up to several ohms above this frequency [14]. The higher frequencies are not very critical because reasonably sized bypass capacitors can be used to provide low impedances.

2. Load regulation. Output voltage changes as a function of load current. Although related to output impedance, especially at high load currents, load regulation depends mainly on the stability of the reference source and the gain of the feedback network [14].

3. Line regulation. Output voltage changes as a function of input voltage. Typical values are less than 0.01 percent change in output voltage for a given change in input voltage [14].

4. Recovery time. The time required for the output voltage to return to within specified regulation limits upon application of a step load change. This parameter is also related to the output impedance, especially at high frequencies where the output impedance tends to be higher. The result is that the high frequency harmonics of the step load change tend to induce a spike of voltage at the output.

5. Drift. Output voltage changes as a function of time, keeping input voltage and load current constant after an initial warm-up period.

Voltage regulators are classified as linear, i.e., the regulating elements operate in the linear region, and switching, i.e., the regulating element is switched on and off so as to produce an average output equal to that required. Linear regulators are configured as either series-pass type or shunt-type depending upon the position of the regulating element with respect to the load. Switching regulators can be switched by means of a regenerative comparator, such as a Schmitt trigger, by more elaborate means using duty cycle/frequency control circuitry containing a comparator, pulse generators and a bistable multivibrator, or by using the unrectified line voltage of a power inverter. The first two methods are usually employed in transistor regulators while the latter is better adapted to SCR

circuits. Simplified circuits of linear and switching voltage regulators are shown in Figs. 4, 5 and 6.

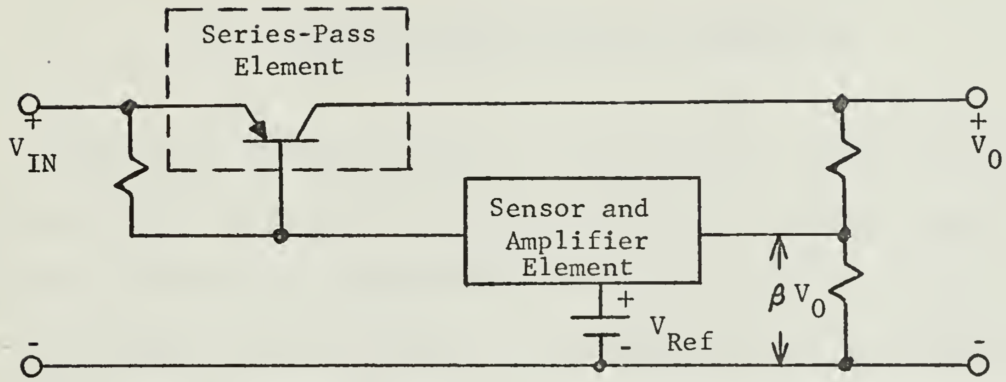



Fig. 4. Basic Transistor Series-Pass Voltage Regulator

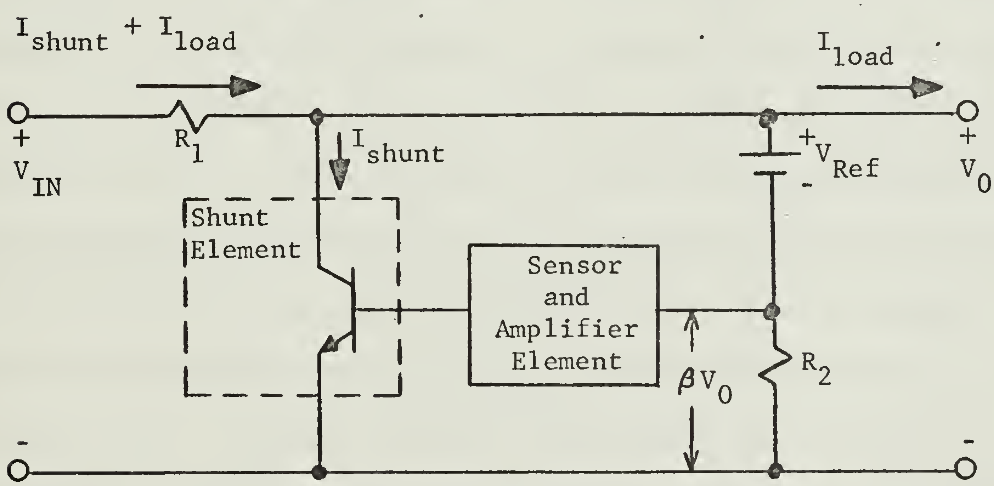



Fig. 5. Basic Transistor Shunt Voltage Regulator

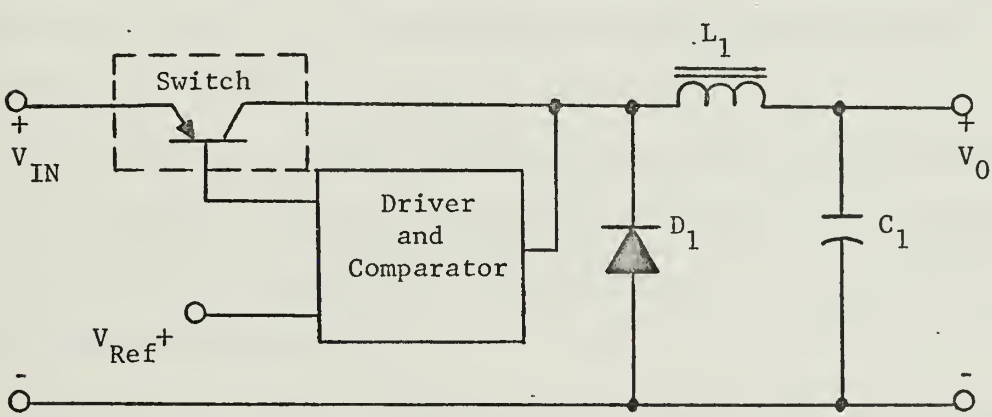


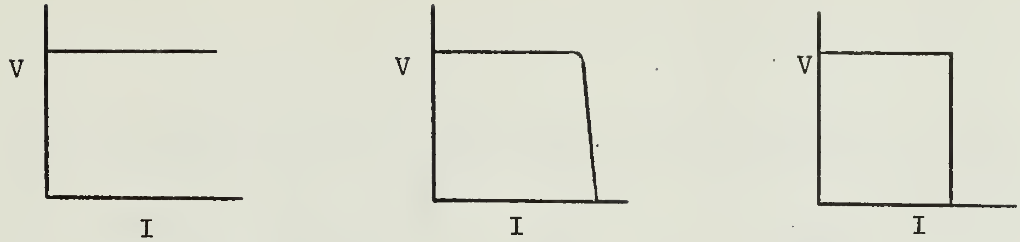

Fig. 6. Basic Transistor Switching Voltage Regulator

## III. LINEAR VOLTAGE REGULATORS

It was noted in the general discussion that the basic types of linear voltage regulators are series-pass and shunt. The shunt regulators are less efficient than the series-pass regulators and therefore were not investigated as part of the power conditioner, but their operation, in short, is as follows: in Fig. 5., it is seen that the shunt element current and the load current pass through resistor $R_1$. If the load changes so as to require greater $I_{load}$, then $V_0$ tends to decrease due to the increased drop across $R_1$. Since $V_0$ tends to decrease, the voltage across $R_2$, $\beta V_0$, tends to decrease. This decrease is sensed and amplified so as to decrease $I_{shunt}$, thereby tending to restore the voltage drop across $R_1$, and, consequently, $V_0$ to their original values. If a load change increases $V_0$, $I_{shunt}$ is increased to return $V_0$ to its original value. Changes in input voltage which tend to change $V_0$, change $\beta V_0$ which is sensed and compared, and the error amplified as noted above, changing $I_{shunt}$ so as to return $I_{load}$ to its proper value and so, too, $V_0$. The inefficiency of this circuit is due to resistive loss in the series resistor $R_1$.

The series-pass voltage regulator can assume different forms - voltage regulating, voltage regulating/current limiting, or voltage regulating/current regulating. The volt-ampere characteristics for these forms are shown in Fig. 7.

Figures 8 and 9 show simple forms of the series-pass regulators. Some circuits replace $Q_1$ with differential amplifiers or operational amplifiers to increase sensitivity and thereby attain better regulation,




Voltage Regulating — Voltage Regulating/ Current Limiting — Voltage Regulating/ Current Regulating

Fig. 7. Series-Pass Voltage Regulator V-I Characteristics

but circuit complexity increases due to balancing when an adjustable output is required. Integrated circuits can easily overcome this problem, by placing the required networks on a single chip. Using discrete components and a transistor sensor/amplifier the series-pass regulator functions in the following manner: If the load changes so that $V_0$ tends to decrease, and hence increases $V_{CE3}$ as in Fig. 10, the current through $R_2$, and so, too, $\beta V_0$, tends to decrease. This decrease is reflected in a decrease of $V_{BE}$ of the sensing transistor, $Q_1$, which decreases $I_{B1}$ and $I_{C1}$. A decrease in $I_{C1}$ decreases the voltage drop across $R_4$ which increases $V_{BE}$ of the pass transistor. $I_{B2}$ and $I_{E3}$ increase accordingly and $V_{CE3}$ decreases, thereby restoring $V_0$ to its proper value and fulfilling the request for increased load. If a load change increases $V_0$, the load current is decreased to return $V_0$ to its proper value. A change in input voltage which tends to increase $V_0$ and hence $I_L$ as in Fig. 11, increases $\beta V_0$ which reflects as an increase to $V_{BE1}$ which increases $I_{B1}$ and $I_{C1}$. An increase in $I_{C1}$ increases the voltage drop across $R_4$ which decreases $V_{BE}$ of the pass transistor, decreasing $I_{B2}$ and $I_L$ and increasing $V_{CE3}$, thereby restoring $V_0$ and $I_L$ to their proper values. If an

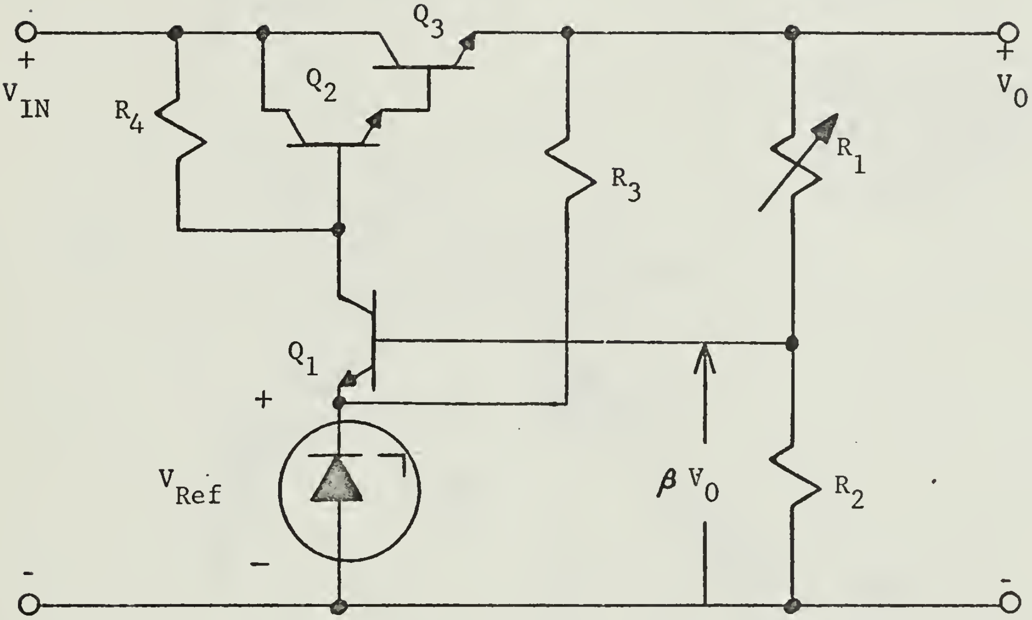



Fig. 8. Series-Pass Voltage Regulator

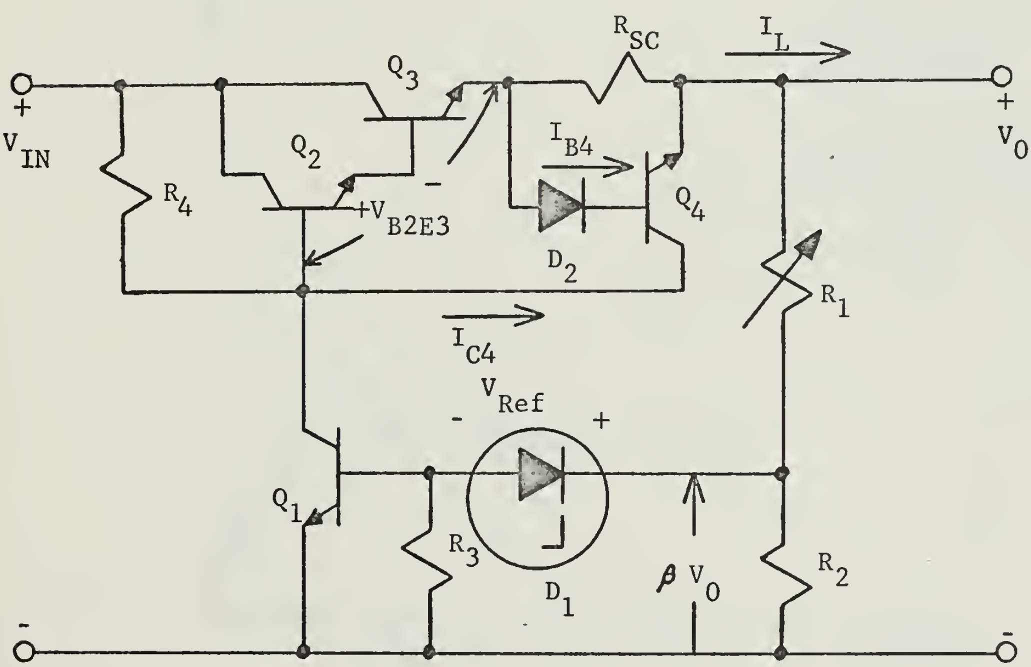



Fig. 9. Series-Pass Voltage Regulator with Current Limiting

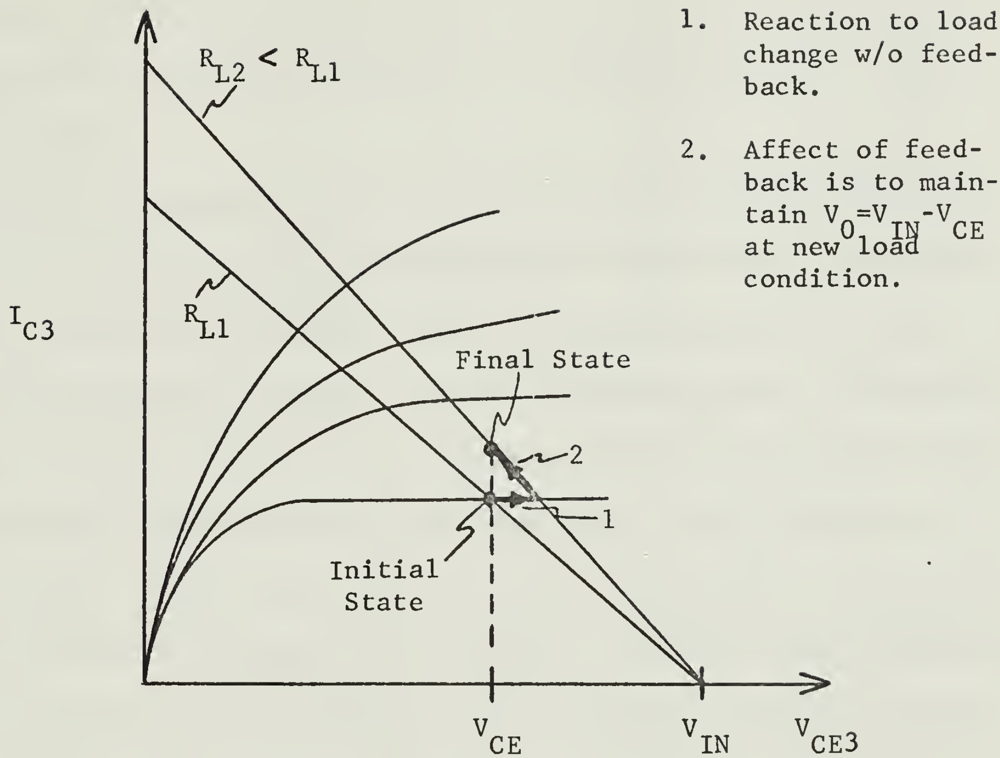



Fig. 10. Pass Transistor Functioning on Load Change

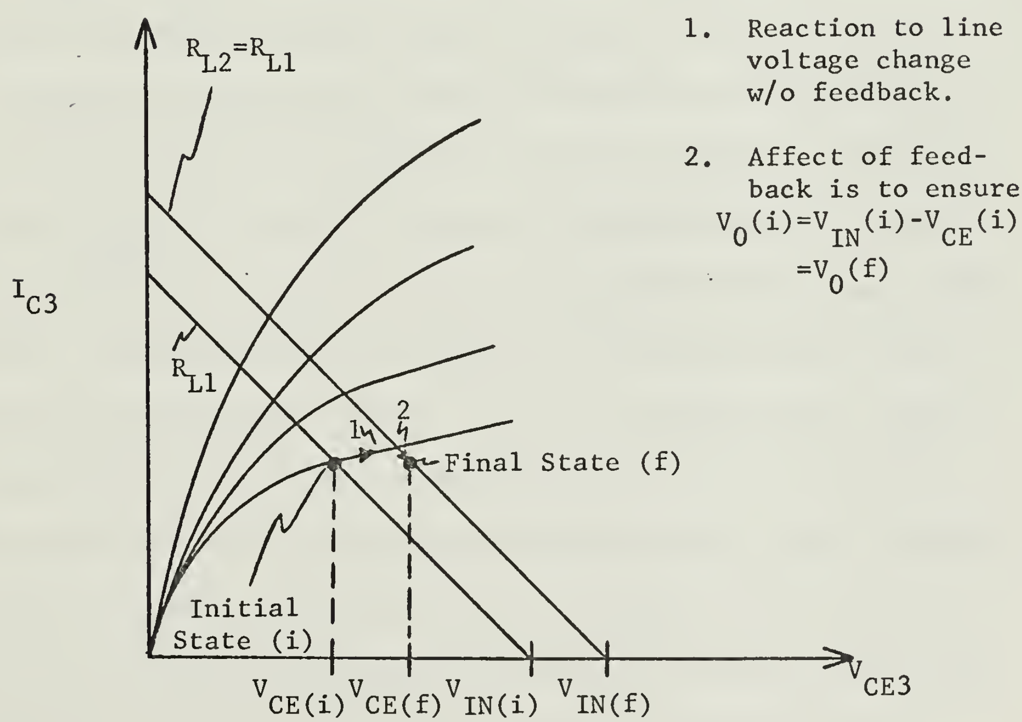



Fig. 11. Pass Transistor Functioning on Voltage Change

input voltage change decreases $V_0$ and the load current, then $I_{E3}$ is increased and $V_{CE}$ is decreased so as to restore $V_0$ and $I_L$ to their proper values.

It can be seen then that the series-pass transistor functions as a variable resistance so as to maintain the output voltage essentially constant, independent of input voltage and/or load changes. Also, operating in the active region it has a fast response time. However, having a resistive quality, the series-pass transistor must dissipate a substantial amount of power especially at low output voltages and high currents. This transistor then must be specified in such a way as to give adequate regulator performance. Certain of these specifications include collector dissipation, $P_T$, maximum collector current, $I_C$ (max), collector leakage current, $I_{CER}$, the current gain parameters, $h_{FE}$ and $h_{fe}$, the saturation voltage, $V_{CE}$ (sat), the collector-to-emitter breakdown voltage $V_{CEO}$ (sus), and second breakdown.

$P_T$ specifies the amount of power which the series-pass transistor can safely dissipate under short circuit conditions, while $I_C$ (max) and $V_{CEO}$ (sus) limit the collector current and input voltage which, under short circuit conditions, are applied to the series-pass transistor. Because of these limitations the regulator must incorporate some overload protection, i.e., over-voltage and/or short-circuit protection, to prevent permanent damage to the regulator. Assuming that the direct energy source voltage differential, no-load to full-load, can be accommodated, over-voltage is not considered a problem. Short circuit protection is necessary, however, and must be incorporated in such a way as to protect the regulator while overloaded, then return to normal operation once the overload

condition is removed. Fuses might be thought to provide the simple solution, i.e., short circuit protection without any degradation of performance; but, fuses are inadequate since their thermal time constants are normally greater than that of the transistor. Some method of current limiting using active devices must be used. One such typical method is shown in Fig. 9 using $D_2$, $Q_4$ and $R_{SC}$. As the load current increases, the voltage across $R_{SC}$ increases. When this voltage is sufficient to activate the $D_2$-$Q_4$ combination and allow $Q_4$ base current, $I_{B4}$, to flow, limiting action begins. The increasing base current, $I_{B4}$, increases the flow of $Q_4$ collector current, $I_{C4}$, which increases the voltage drop across resistor $R_4$. This voltage change tends to drive the voltage between the base of $Q_2$ and the emitter of $Q_3$, $V_{B2E3}$, toward cut-off. This action continues until $V_0 = 0$. The amount of short circuit current is determined by adjusting $R_{SC}$.

Low leakage currents, necessary for thermal stability, are a function of the semiconductor material and are usually negligible in silicon transistors which exhibit relatively low temperature effects. Second breakdown is a function of the geometry of the transistor and relates to a power pulse, collector voltage and current, which causes destruction of the transistor because of current crowding. Current crowding, i.e., increased current density near the rim of the emitter and decreased current density near the center of the emitter for a given current, causes localized heating, hot spots, which tends to destroy the transistor even though neither $V_{CEO}$ (sus) nor $I_C$ (max) are reached. In an effort to improve transistors, manufacturers are using techniques which maximize emitter perimeters for given

emitter areas. Second breakdown information in the form of power ratings may be listed in transistor technical data, but in case it is not, certain tests listed in Ref. 14 may be performed.

$V_{CE}$ (sat) assists in determining the minimum input voltage for a given output voltage. The current gain parameters $h_{FE}$ and $h_{fe}$ determine the current drive required for specific loads while a high $h_{fe}$ means a low output impedance.

Considering, then, the regulator parameters mentioned in Section II and the above transistor parameters, the circuits in Figs. 12 and 13 were breadboarded and tested. A summary of the results is listed in Table I while the characteristic curves are included in Appendix A. The $\mu$A723C of Fig. 13 is a monolithic voltage regulator consisting of a temperature compensated reference amplifier, error amplifier, power series-pass transistor and current limit circuitry which can operate from $0^{o}C$ to $70^{o}C$.

It can be seen that the tested discrete regulator of Fig. 12 is a replica of the circuit in Fig. 9. The latter circuit was chosen over that of Fig. 8 because current limiting applied to the circuit of Fig. 8 caused the base-emitter voltage of the sense transistor to go beyond the breakdown voltage of that junction. There was no chance of this happening in the circuit under test. Otherwise, both circuits gave similar results.

A review of the above results shows that the load regulation and efficiency of the IC and discrete regulators are approximately the same. Neither circuit gives the .05% load regulation required in Section I. The line regulation, average temperature coefficient of output voltage and output impedance of the IC regulator are considerably

| Parameter | Conditions | IC | Discrete | Units |
| --- | --- | --- | --- | --- |
| Line Regulation | $I_L$=2.14A | 0.02 | 0.26 | $\%V_0$ |
| $V_0$=28V | $I_L$=1.6A | 0.02 | 0.05 | |
| 32V $\leq V_{IN} \leq$ 39V | $I_L$=0.8A | 0.02 | 0.01 | |
| $T_A$=27$^\circ$C | | | | |
| $V_0$=24V | $I_L$=2.5A | 0.01 | 0.10 | $\%V_0$ |
| 28V $\leq V_{IN} \leq$ 39V | $I_L$=1.9A | 0.01 | 0.06 | |
| $T_A$=27$^\circ$C | $I_L$=0.94A | 0.01 | 0.03 | |
| Load Regulation | | | | |
| $V_0$=28V | | | | |
| $V_{IN}$=33V | 0.8A $\leq I_L \leq$ 2.14A | 0.14 | 0.12 | $\%V_0$ |
| $T_A$ =27$^\circ$C | | | | |
| $V_0$=24V | | | | |
| $V_{IN}$=33V | | | | |
| $T_A$=27$^\circ$C | 0.94A $\leq I_L \leq$ 2.5A | 0.20 | 0.18 | $\%V_0$ |
| $T_A$=63$^\circ$C | 0.94A $\leq I_L \leq$ 2.5A | 0.32 | 0.25 | $\%V_0$ |
| Average Temperature Coefficient of Output Voltage | 27$^\circ$C $\leq T_A \leq$ 63$^\circ$C | 0.03 | 0.06 | %/$^\circ$C |
| Efficiency (max) | | | | |
| $V_{IN}$=33V; $T_A$=27$^\circ$C | $V_0$=28V | 84.3 | 84.1 | % |
| | $V_0$=24V | 72.1 | 72.0 | % |
| Output Impedance | | | | |
| $V_{IN}$=33V; $T_A$=27$^\circ$C | f $\leq$ 1KHz | 0.05 | 0.1 | ohms |
| $V_0$ =24V; $I_L$=1.6A | | | | |

Table I. Linear Regulator Results

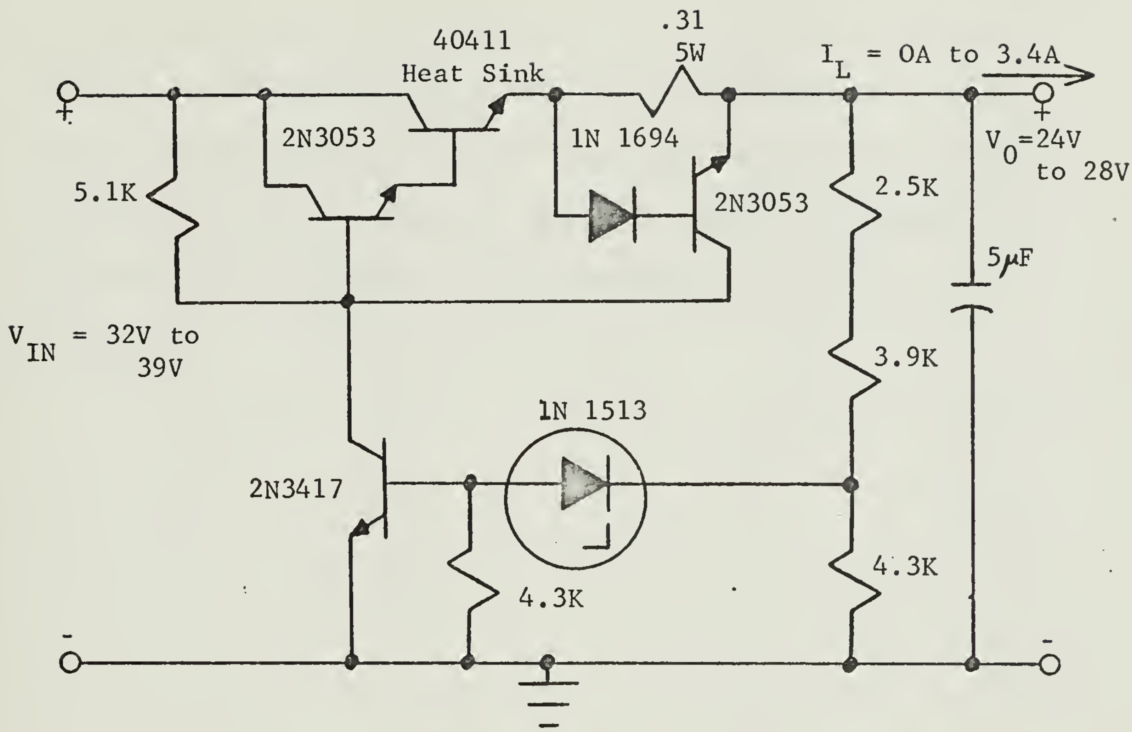



Fig. 12. Discrete Series-Pass Linear Voltage Regulator

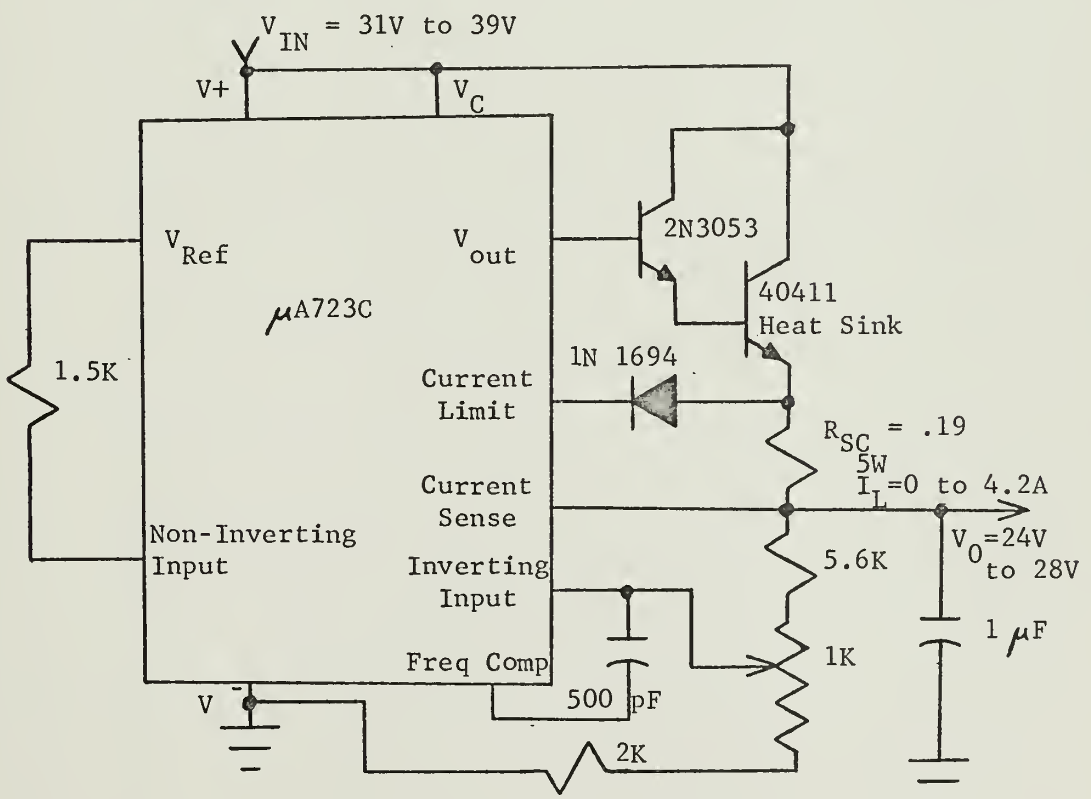



Fig. 13. IC Series-Pass Linear Voltage Regulator

better than the discrete regulator, as expected. The discrete regulator has the advantage of being able to withstand a higher input voltage limited by the pass transistor and sense transistor breakdown voltage and power ratings, while the IC is limited to $V_{IN}$=40V by specification. Recovery time and drift were not investigated.

## IV. SWITCHING VOLTAGE REGULATORS

Figure 6 showed the basic circuit configuration for a transistor switching voltage regulator wherein the transistor acts as a switch, usually operating between saturation, if given enough base drive, and cut-off. A rectangular wave of voltage results at the transistor-side of the inductor, the average voltage of which is equal to the desired output. This rectangular wave is filtered by the diode-inductor-capacitor combination so that the load receives an ac ripple output about the desired dc level. A simplified diagram of the switching-filtering circuit and the associated time waveforms appear in Fig. 14. A closed switch approximates a saturated transistor while an open switch approximates a cut-off transistor. Assuming a steady state condition and considering the switch closed at time $t=t_o$, the circuit functions as follows: $V_{D1}=V_0'$, therefore, diode D1 is reversed biased and current starts to increase its flow through the inductor L, where

$$(di_L/dt) = (1/L) \tag{4-1}$$

and

$$v_L = V_0 - V_0' . \tag{4-2}$$

This current increase feeds the load and charges the capacitor C until a level of output voltage determined by the sensing circuit is reached and the transistor switch is turned off at time $t_1$. With the switch off, the capacitor C discharges through the load and the diode D1 is forward biased allowing a current path for the energy stored in the inductor to discharge through the load. Then $V_{D1}=-V_{Diode}$, the

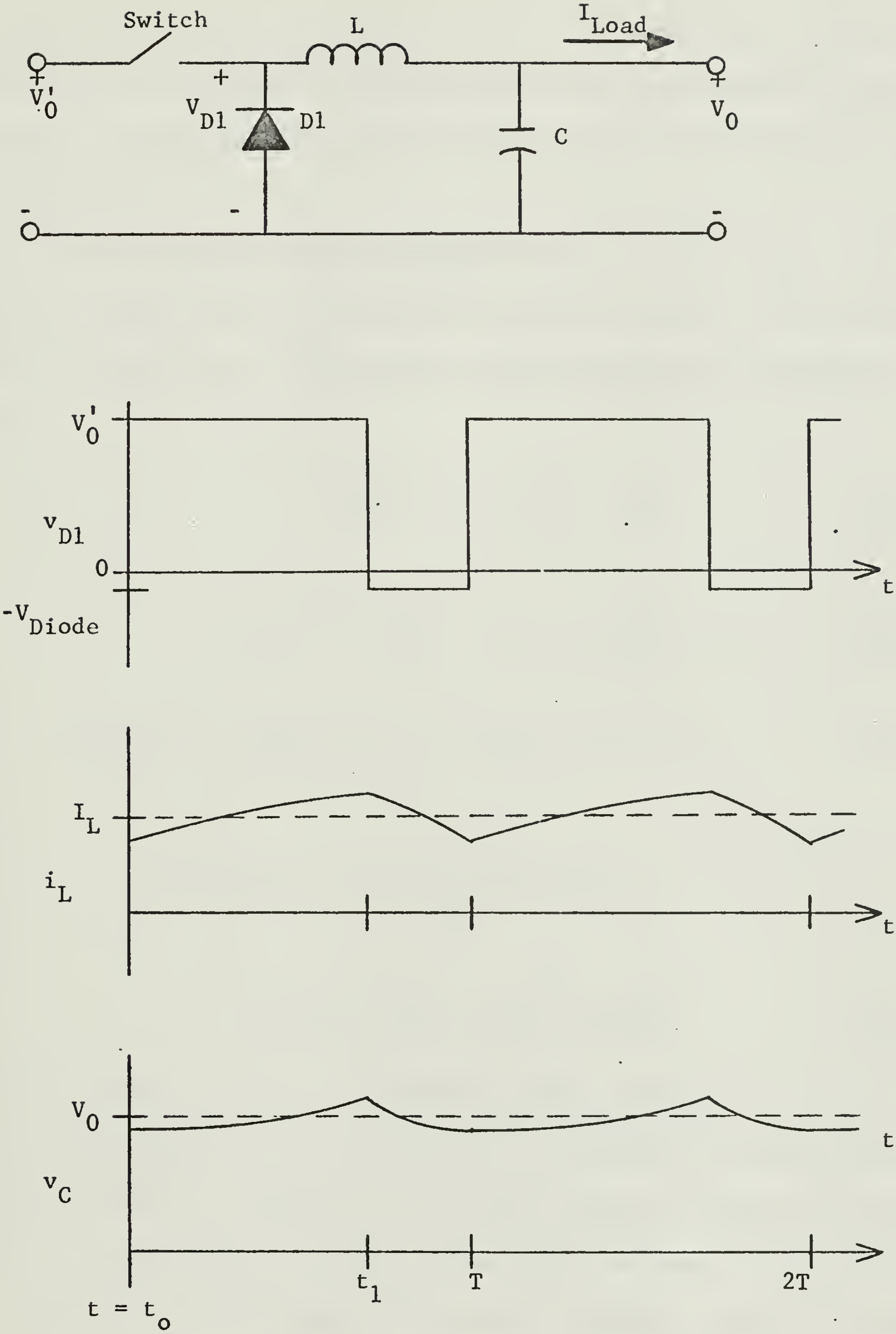



Fig. 14. Switching-filtering Circuit and Associated Time Waveforms

voltage drop for a forward biased diode. The capacitor discharges until a level of the output voltage determined by the sensing circuit is reached. The transistor switch is turned on at time T and the cycle repeats itself.

Considering negligible resistive losses in the inductor, the average output voltage, $V_0$, can be considered equal to the average diode voltage, $V_{D1}$. The average value then is easily computed from

$$V_{avg} = (1/T) \int_{t_o}^{T} v\,dt \tag{4-3}$$

$$V_{avg} = (1/T) \int_{t_o}^{t_1} v\,dt + (1/T) \int_{t_1}^{T} v\,dt \tag{4-4}$$

$$V_{avg} = (1/T)\ [V_0'(t_1 - t_o) + (-V_{Diode})(T - t_1)] \tag{4-5}$$

Let

$$t_1 - t_o = t_{on}\ ,\ T - t_1 = t_{off}\ \text{and}\ V_0 = V_{avg}$$

then

$$V_0 = (t_{on}/T)V_0' - (t_{off}/T)V_{Diode} \tag{4-6}$$

By varying the duty cycle, conduction angle, of the pass transistor, the output voltage can be varied, e. g., if the output voltage tends to decrease below the reference level, the conduction angle will increase; and, vice-versa for an increase of the output voltage above reference.

The primary advantage in using the switching-regulator instead of the linear regulator is the higher efficiency of the former because the pass transistor is operated in its two most efficient states -- saturation and cut-off. Regulation and recovery time are not as

good, however, as those obtainable with the linear regulator.

The pass transistor parameters remain the same as those for the linear regulator with the exception that now the switching times, rise time, $t_r$, and fall time, $t_f$, are of utmost importance. To accommodate a wide range of input voltage and output current and still get good regulation, the conduction angle must be variable from at least 10 to 90 percent [14]. This means that the minimum pulse width is one-tenth of the period, T/10. For low switching losses, a minimum amount of time must be spent in the active region. Then $t_r$ and $t_f$ must be much less than the minimum pulse width, or

$$t_r \leq t_f \leq T/100. \qquad (4\text{-}7)$$

The filter network, as can be seen from the previous discussion, forms an integral part of the switching regulator. If a resistive-capacitive (RC) filter were used instead of the commutating diode, inductor, capacitor filter, a dramatic lessening of efficiency would result because the resistance would have to be large enough to limit the peak current to a safe transistor level. A purely inductive filter would give rise to a dangerous voltage spike when the pass transistor goes to cut-off, or when there is an abrupt change in load, because the current through the inductor cannot change instantaneously; also, for light loads, i.e., the load current less than one ampere, the size of the inductance must be increased considerably to store sufficient energy to provide continuous current to the load since

$$\text{Energy stored} = \tfrac{1}{2}\ LI^2. \qquad (4\text{-}8)$$

The inductor-capacitor filter in conjunction with the commutating diode provides the following advantages over the RC or inductive

filters [14].

1. No resistive (lossy) elements.

2. The inductor limits peak transistor currents.

3. The commutating diode prevents dangerous inductor-induced voltage spikes by providing a path for the inductor current after the pass transistor is switched off.

4. The capacitor maintains the appropriate output voltage, at light loads when the inductor current becomes discontinuous, thereby obviating the need to have an oversized inductor.

The type of core required for the inductor depends on the load current and frequency of operation. The higher the frequency of operation of the switching regulator the better the regulation, but the core losses and transistor switching times limit this frequency. Typical switching regulators operate in the upper audio frequency range 10 KHz to 20 KHz and use ferrite pot cores [9 and 13], or other higher frequency cores, e.g., permalloy-dust toroidal cores. Exact selection of core type can be made by research in appropriate specification sheets and catalogs of core manufacturers, such as Magnetics, Inc., or Arnold Engineering Co. The commutating diode should be a fast-switching type in order to prevent excessive voltage transients at the transistor. Any switching transients should be investigated with respect to transistor second breakdown, as noted in Section III.

To investigate the performance of a switching regulator in accordance with Section II and the above discussion, the circuits of Figs. 15 and 16 were breadboarded and tested. A summary of the results is listed in Table II, while characteristic curves are included

in Appendix B. These results compare favorably with similar pulse-width modulated systems designed and tested in Refs. 9 and 11. It can be seen that the switching regulators are much more efficient than linear regulators, but provide much less regulation. Also, an output voltage ripple is present whether or not there is a ripple at the input. The basic design concept of the discrete regulator was obtained from Ref. 9 while the Schmitt trigger was designed using principles noted in Ref. 6. The IC regulator was configured using Ref. 13 as a guide. The commutating diode was not a fast-switching diode and led to a transient voltage spike when the pass-transistor was turned-on. The inductor, $L_1$, is 82 turns of #20 enameled copper wire wound on Arnold permalloy toroidal core A254168-2.

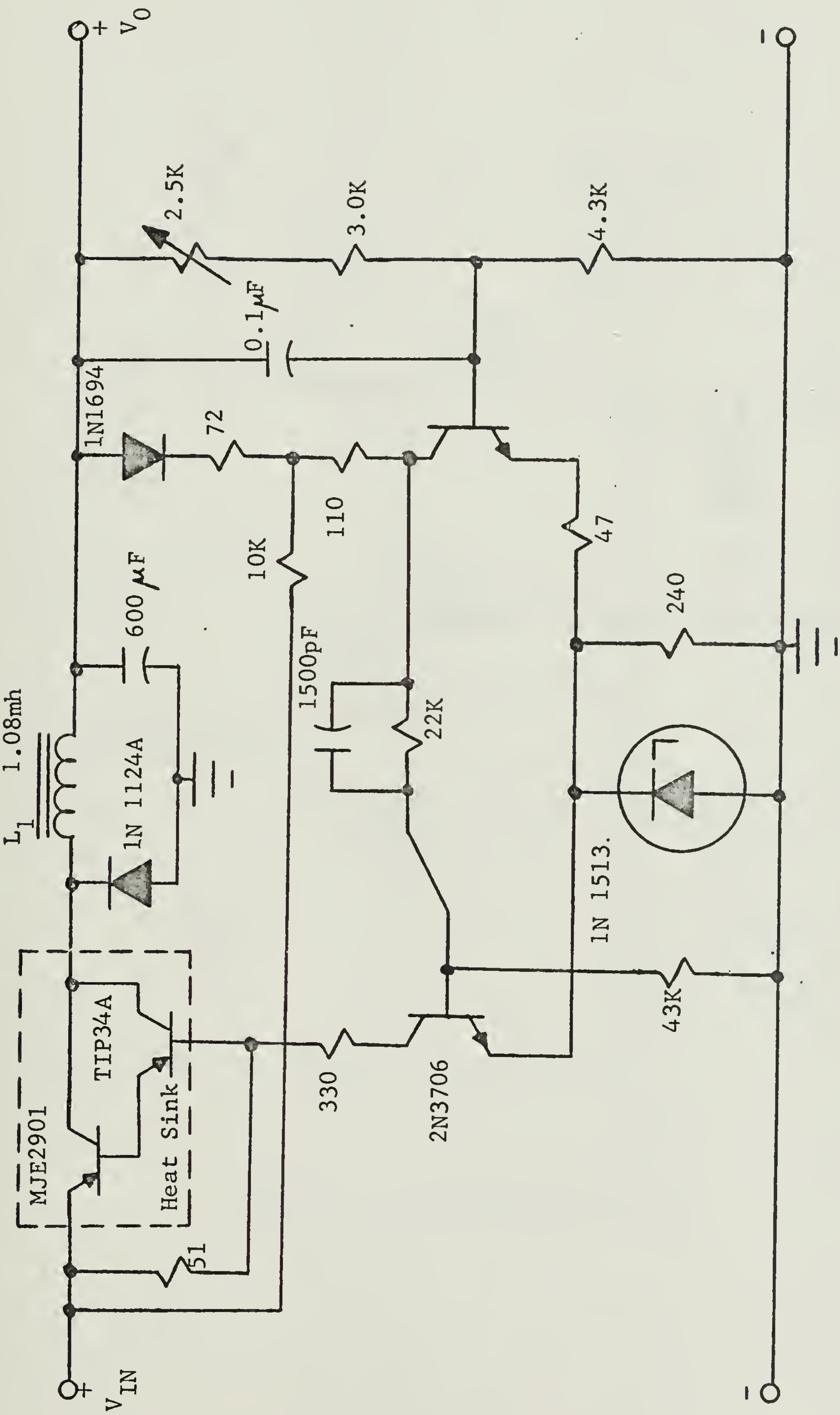



Fig. 15. Discrete Switching Voltage Regulator

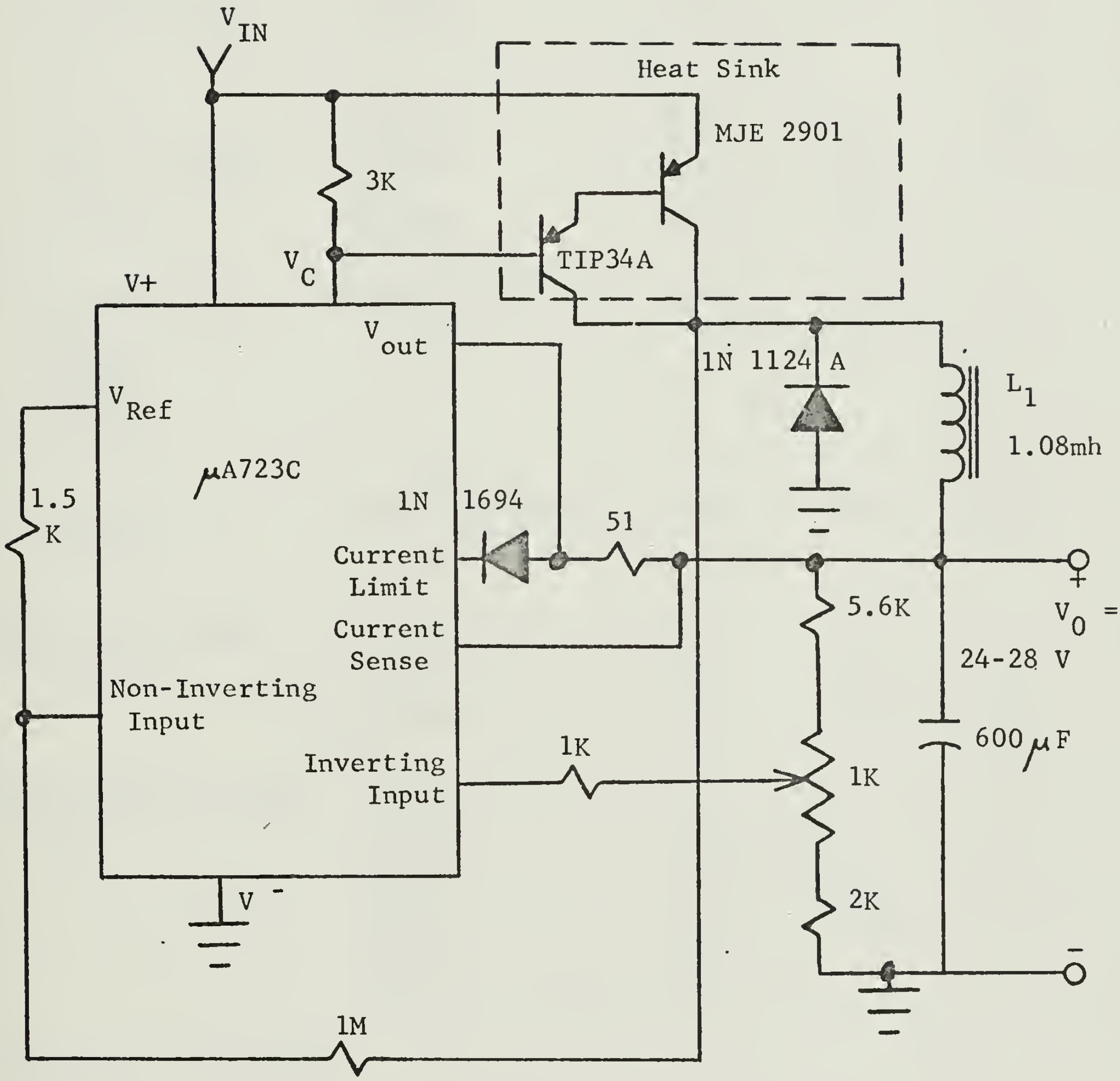



Fig. 16. IC Switching Regulator

| Parameter | Conditions | IC | Discrete | Units |
|---|---|---|---|---|
| Line Regulation* | $I_L$=2.14A | 0.8 | 6.0 | $\%V_0$ |
| $V_0$=28V | $I_L$=1.6A | 0.6 | 6.0 | |
| $31V \leq V_{IN} \leq 39V$ | $I_L$=0.8A | 0.3 | 2.0 | |
| $T_A$=27°C | | | | |
| $V_0$=24V | $I_L$=2.5A | 0.6 | 2.5 | $\%V_0$ |
| $29V \leq V_{IN} \leq 39V$ | $I_L$=1.9A | 1.4 | 2.5 | |
| $T_A$=27°C | $I_L$=0.94A | 0.8 | 2.5 | |
| Load Regulation | $0.8A \leq I_L \leq 2.14A$ | 0.7 | 0.15 | $\%V_0$ |
| $V_{IN}$# | | | | |
| $V_0$=28V | | | | |
| $T_A$=27°C | | | | |
| $V_0$=24V | $0.94A \leq I_L \leq 2.5A$ | 0.9 | 0.28 | $\%V_0$ |
| $T_A$=27°C | | | | |
| Efficiency (Max) | | | | |
| $V_{IN}$# | $V_0$=28V | 93.7 | 88.2 | % |
| | $V_0$=24V | 92.3 | 84.4 | % |
| Output Ripple (Max) | | | | |
| $V_{IN}$# | $V_0$=28V | 1.0 | 0.22 | V |
| | $I_L$=2.14A | | | |
| | $V_0$=24V | 1.2 | 0.05 | V |
| | $I_L$=2.5A | | | |
| Frequency of Operation | | | | |
| $V_{IN}$# | | | | |
| $V_0$=28V | $0.8A \leq I_L \leq 2.14A$ | 1.3 to 0.9 | 13.3 to 10.0 | KHz |
| $V_0$=24V | $0.94A \leq I_L \leq 2.5A$ | 1.0 to 1.2 | 1.5 to 3.5 | KHz |

*The discrete regulator obtained better line regulation over a lesser band of $V_{IN}$ as shown in Appendix B.

#$V_{IN}$ = 31V (IC); $V_{IN}$ = 33V (Discrete)

Table II. Switching Regulator Results

## V. POWER CONDITIONER FEASIBILITY AND SUMMARY

Investigating the operation of a dc-dc converter is not within the scope of this paper, but the feasibility of using such a converter in conjunction with the tested regulators of Sections III and IV will be developed. To accomplish such a study, various equations concerning power efficiencies and voltage variations and characteristics of converter operation as expressed in Refs. 12 and 14 were used.

Petty [12] developed a turns ratio for the output transformer of a one or two transformer push-pull converter

$$N_{sec} = n\, N_{pri} \tag{5-1}$$

where

$$n^2 = R_{sec}/R_{pri} \tag{5-2}$$

$$R_{sec} = V_{sec}/I_{sec}, \tag{5-3}$$

and $R_{pri} = (V_{supply} - V_{CE}(sat))V_{supply}\,\eta\,/V_{sec}I_{sec}$. (5-4)

By appropriate substitution it can be found that

$$n = V_{sec}/\left[(V_{supply} - V_{CE}(sat))\;V_{supply}\,\eta\right]^{\frac{1}{2}}. \tag{5-5}$$

Petty also showed that circuit efficiency, $\eta$ , fell between 60% and 80% depending on load, with the two transformer converter showing a flatter efficiency versus load characteristic. The converters he tested switched at frequencies below 2KHz. Since those tests, its been found that transformer converters can operate at higher frequencies, with appropriate transformer cores and switching transistors with

low $V_{CE}$ (sat) providing pre-rectification efficiencies in excess of 90% [14].

Since the power into the system of Fig. 2 is 80 watts, the power out before rectification, assuming 90% efficiency, is 72 watts. The power lost in full-wave bridge rectification is

$$P_{Rect} = 2V_{Diode}I_{Diode} \tag{5-6}$$

where $V_{Diode} \approx 1.2V$ for power rectifiers. For $I_{Diode} = 2.1A$, $P_{Rect}$ is 5.04W. This means the power to the voltage regulator is approximately 67W. The voltage regulator efficiency

$$\eta_{reg} = P_{out}/P_{in}\ (reg) \tag{5-7}$$

must be

$$\eta = (60/67)100 = 89.5\%.$$

The linear voltage regulators have a maximum efficiency of 84%, therefore, a combination dc-dc converter-linear voltage regulator power conditioner, in accordance with the specifications of Section I, is not possible. The IC switching voltage regulator with efficiencies greater than 90% is the only regulator tested which qualifies for the power conditioner.

Before any conclusions can be drawn, the power source voltage variation effects must be checked. Taking the input voltage to the switching regulator at 40 volts, to prevent overvoltage, the secondary voltage of the output transformer is

$$V_{sec} = 2V_{Diode} + V_{IN}\ (reg) \tag{5-8}$$

or

$$V_{sec} = 42.4 \text{ volts}.$$

Using the turns ratio equation 5-1 with

$V_{supply} = 10V$ $\qquad$ $V_{sec} = 42.4V$

$V_{CE}(sat) = 0.75V$ $\qquad$ $\eta = .90$

it can easily be shown that

$$N_{sec} = 4.65\ N_{pri}\ .$$

Using this turns ratio, assuming a power source voltage of 6 volts instead of 10 volts and solving equation 5-5 for $V_{sec}$, it can be found that the input voltage to the regulator is 22.3 volts which is inadequate. Using a minimum input voltage to the regulator of 31 volts it was found that the power source voltage variation must be limited between 7.93V and 10V. This may not be altogether unreasonable for a fuel cell if it is reconfigured and the 15 watts feedback is properly used to maintain material and heat balances.

The following, then, is a summary of the results described previously.

1. Linear and switching voltage regulators can be configured to provide an adjustable output voltage of 24 to 28 volts.

2. Linear regulators provide better regulation than switching regulators but are less efficient.

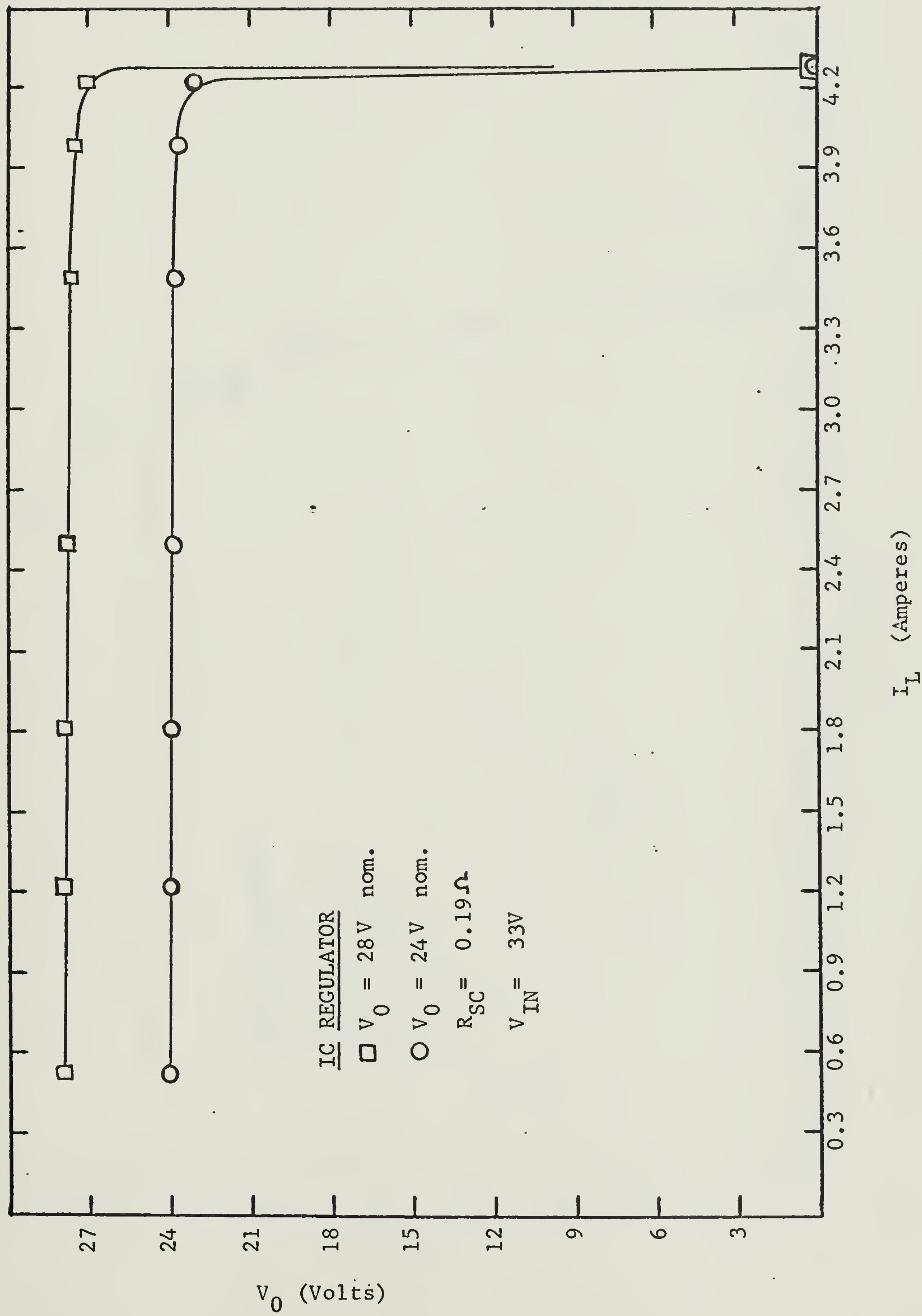
3. Linear regulators demonstrated no output ripple, while switching regulators provided an output ripple dependent on the circuitry.

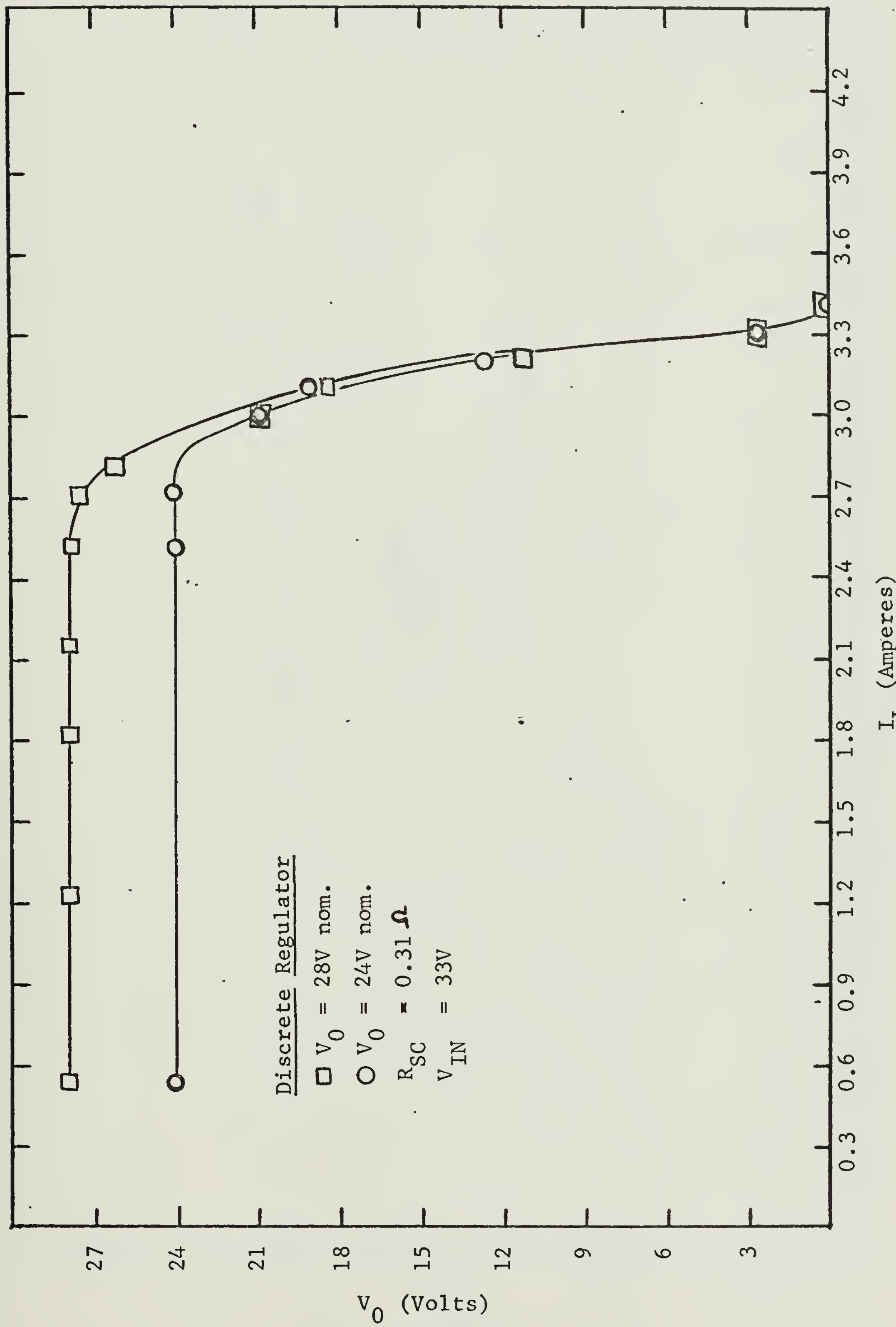
4. IC regulators provided a versatility of operation without complicated discrete circuit components.

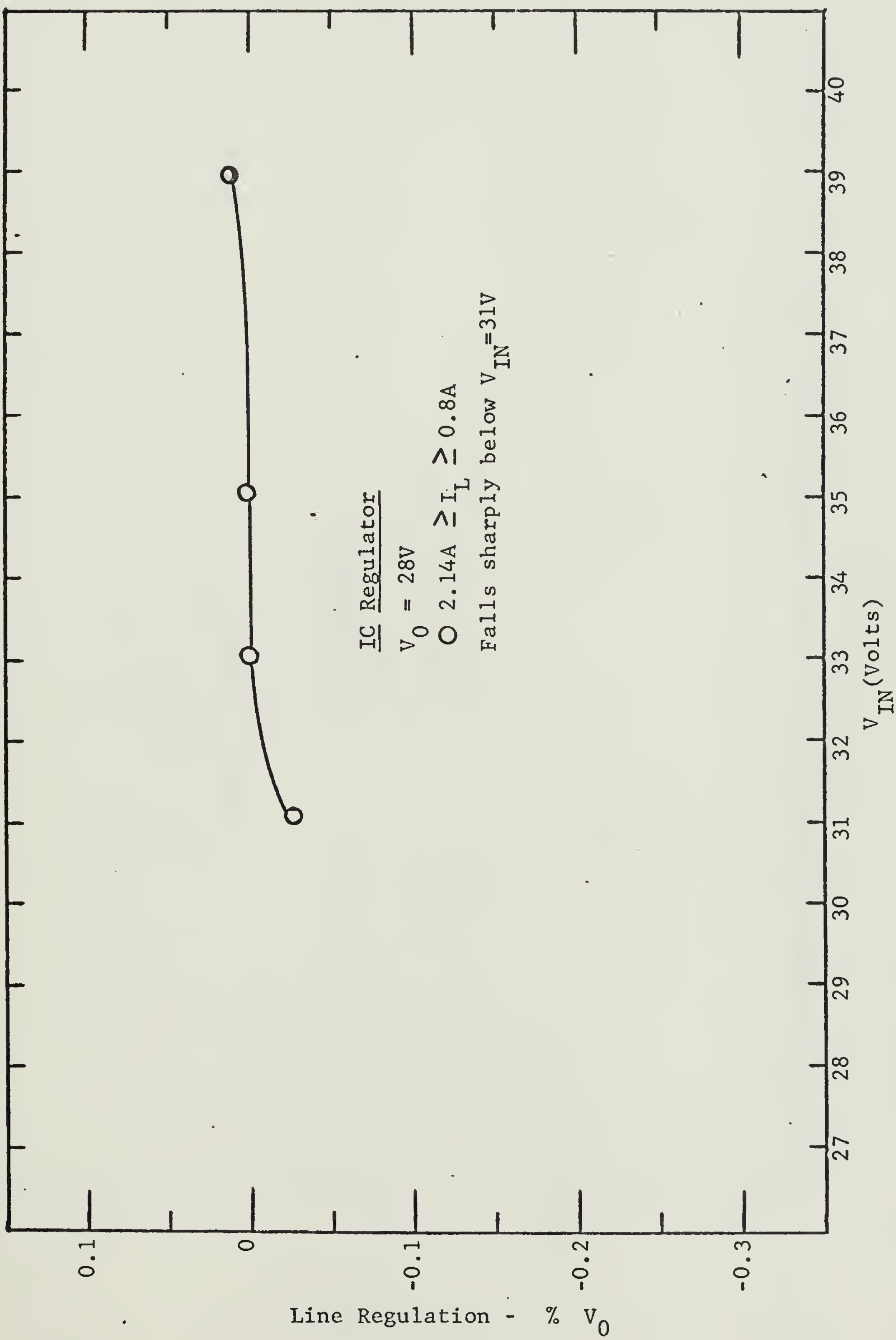
5. It is feasible to configure a push-pull dc-dc converter/ switching-voltage regulator power conditioner with more than 75% efficiency and adjustable 24 to 28 volts output at the cost of voltage regulation and output ripple.

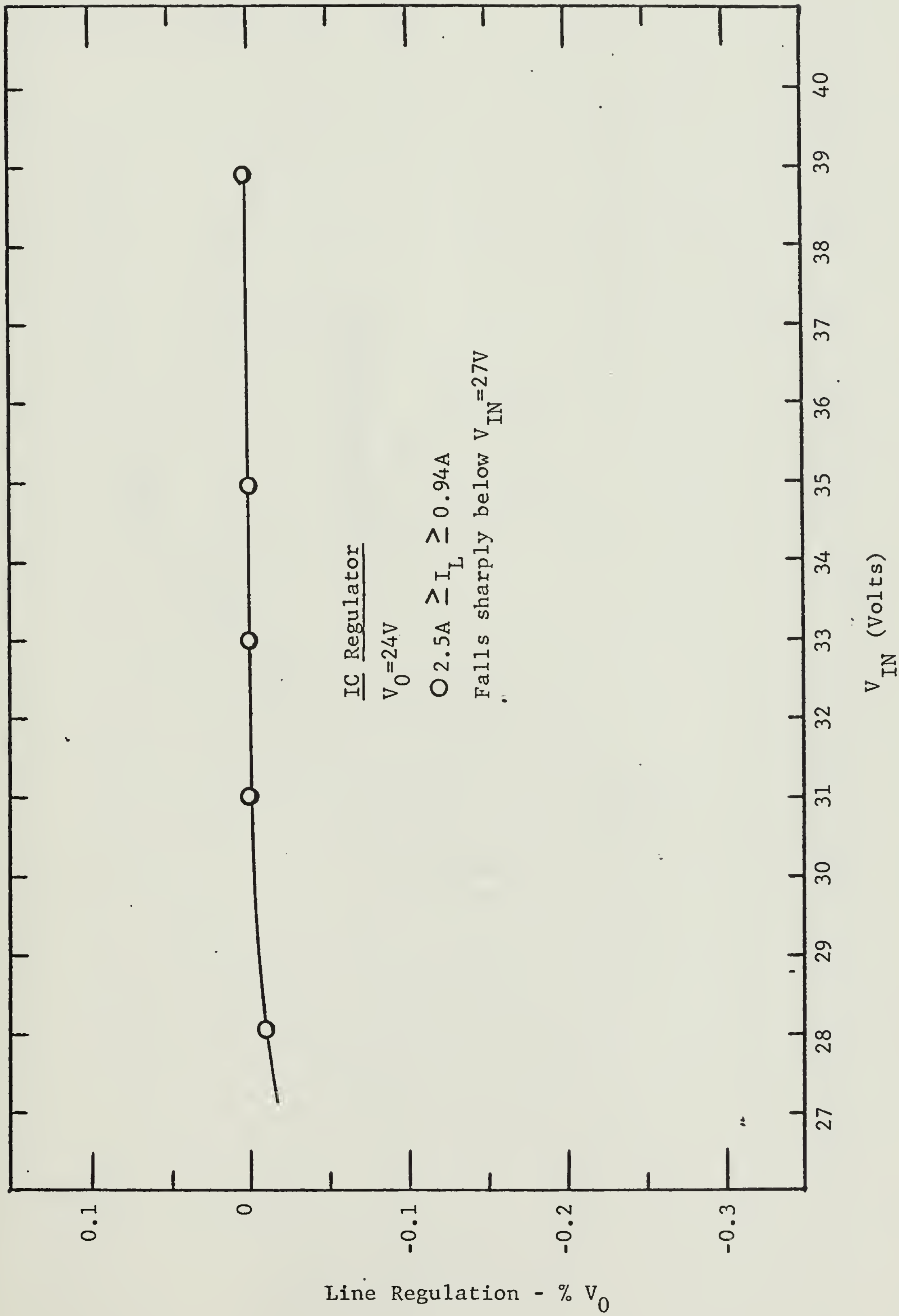
## APPENDIX A

### Characteristic Curves of Linear Regulators

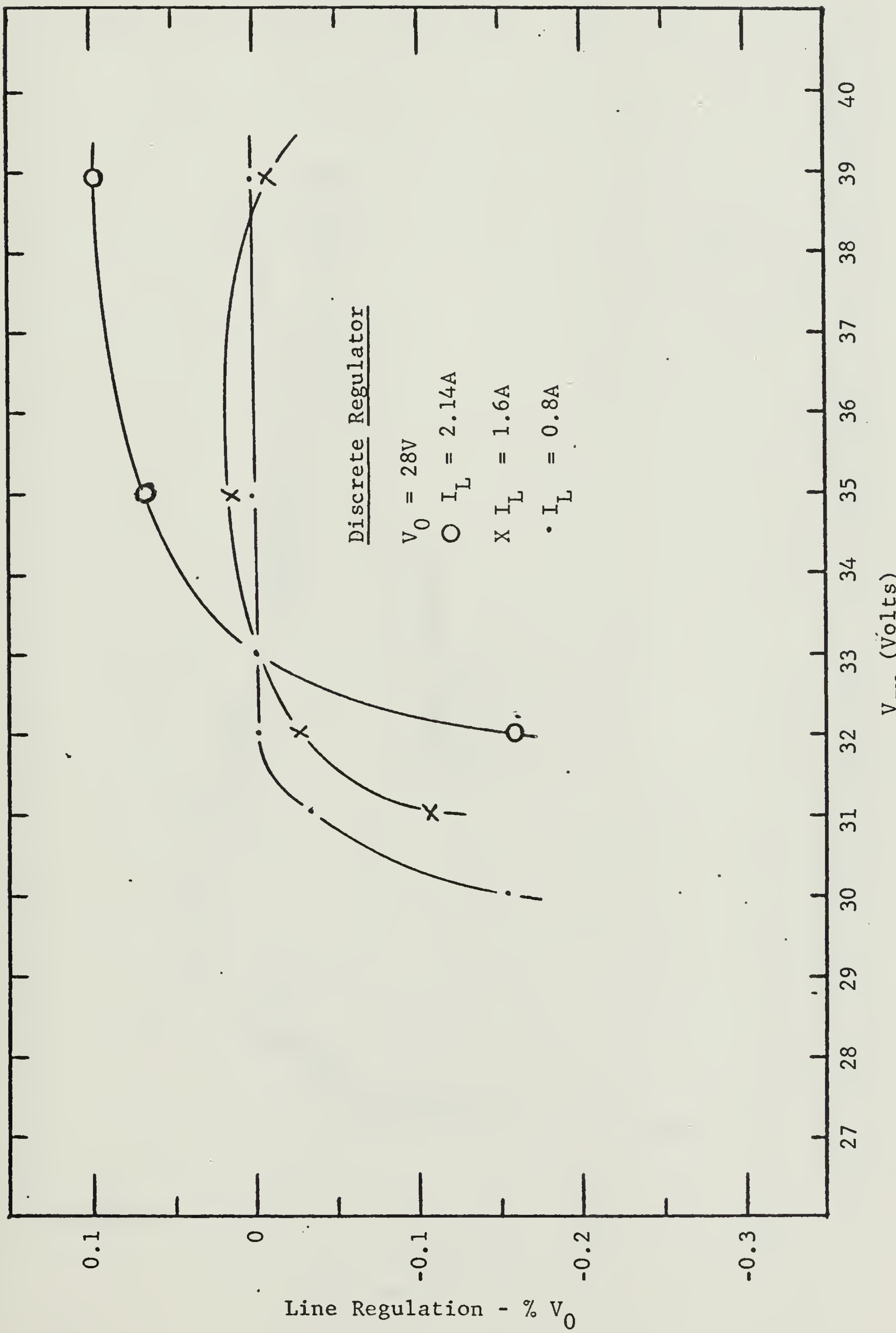

IC REGULATOR
□ $V_0$ = 28 V nom.
○ $V_0$ = 24 V nom.
$R_{SC}$ = 0.19 Ω
$V_{IN}$ = 33V
$V_0$ (Volts)
27
24
21
18
15
12
9
6
3
$I_L$ (Amperes)
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
3.3
3.6
3.9
4.2

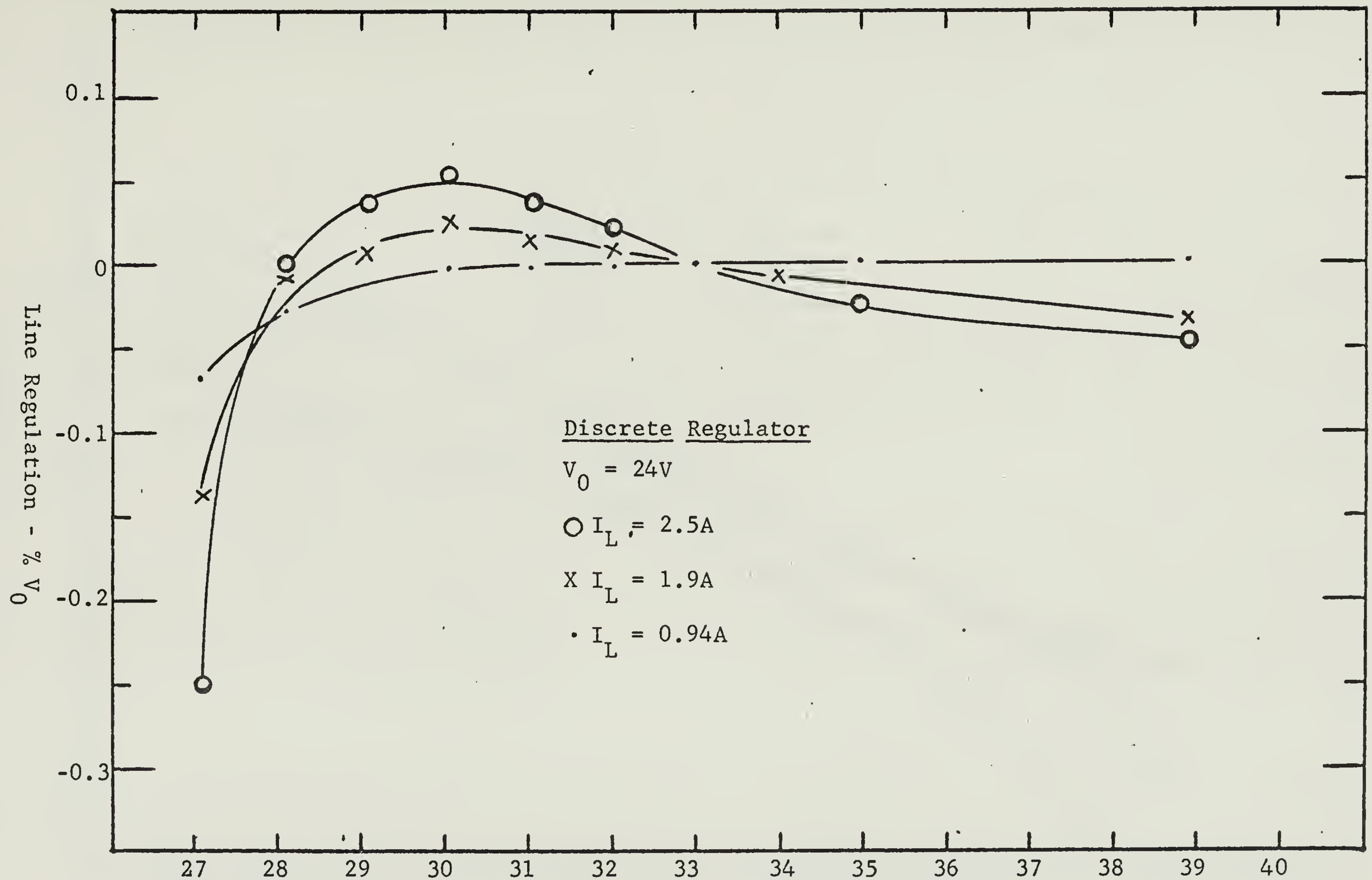

Discrete Regulator
$V_O$ = 28V nom.
$V_O$ = 24V nom.
$R_{SC}$ = 0.31 Ω
$V_{IN}$ = 33V
$V_O$ (Volts)
27
24
21
18
15
12
9
6
3
$I_L$ (Amperes)
0.3
0.6
0.9
1.2
1.5
1.8
2.1
2.4
2.7
3.0
3.3
3.6
3.9
4.2

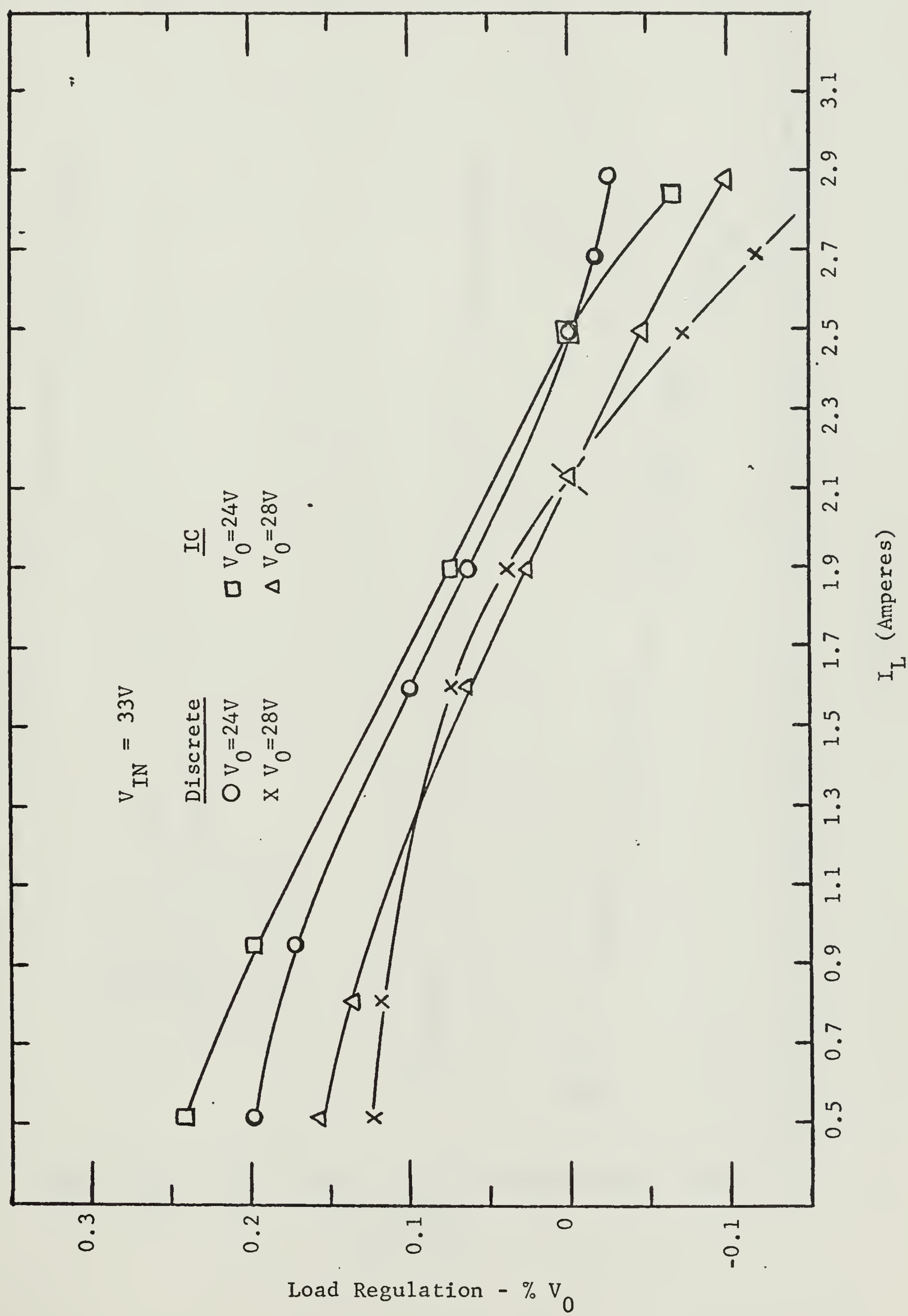

IC Regulator
$V_0 = 28V$
O 2.14A $\geq I_L \geq$ 0.8A
Falls sharply below $V_{IN}$=31V
27
28
29
30
31
32
33
34
35
36
37
38
39
40
$V_{IN}$(Volts)
0.1
0
-0.1
-0.2
-0.3
Line Regulation - % $V_0$



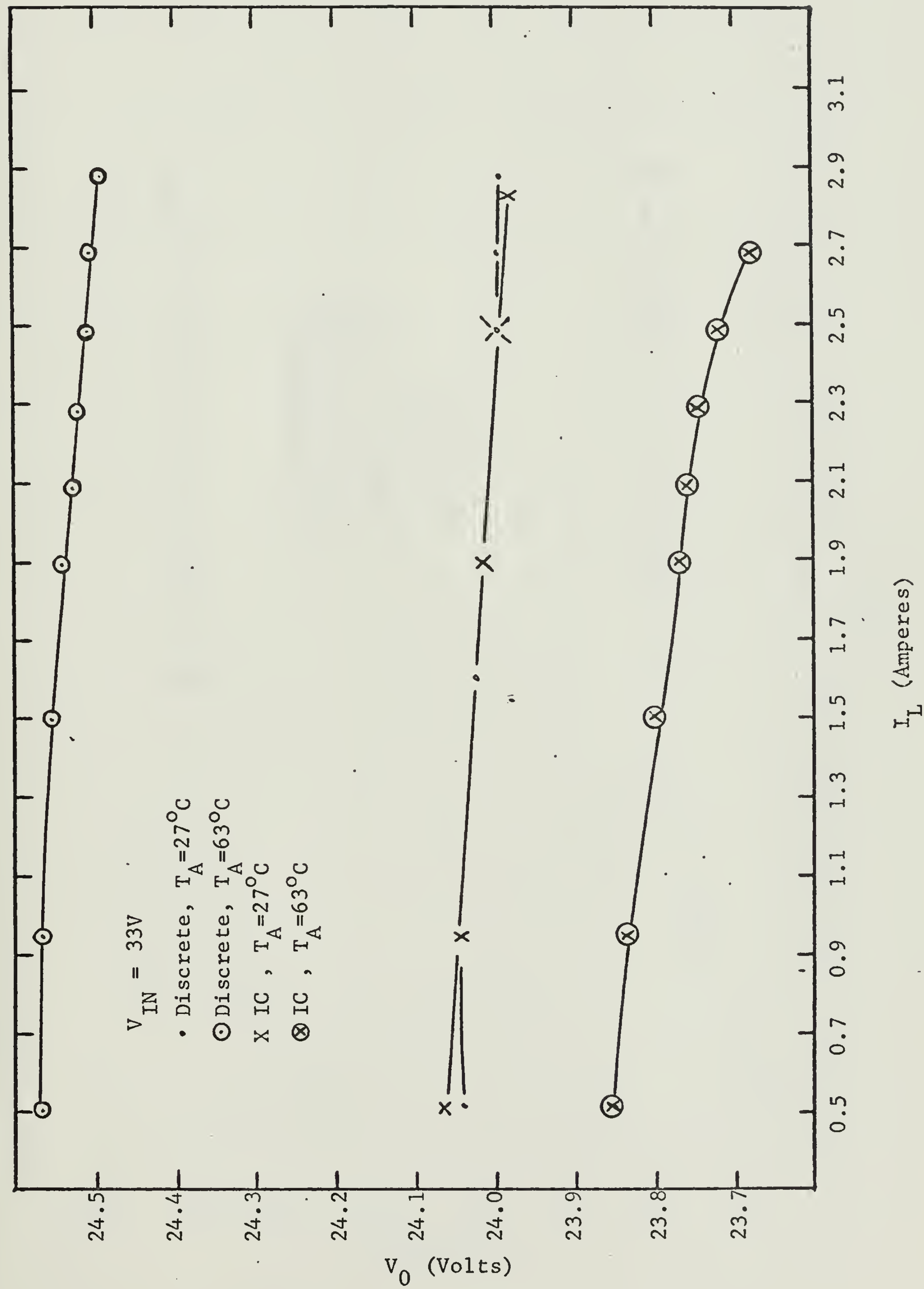
IC Regulator
$V_0$=24V
○ 2.5A ≥ $I_L$ ≥ 0.94A
Falls sharply below $V_{IN}$=27V
27
28
29
30
31
32
33
34
35
36
37
38
39
40
$V_{IN}$ (Volts)
0.1
0
-0.1
-0.2
-0.3
Line Regulation - % $V_0$

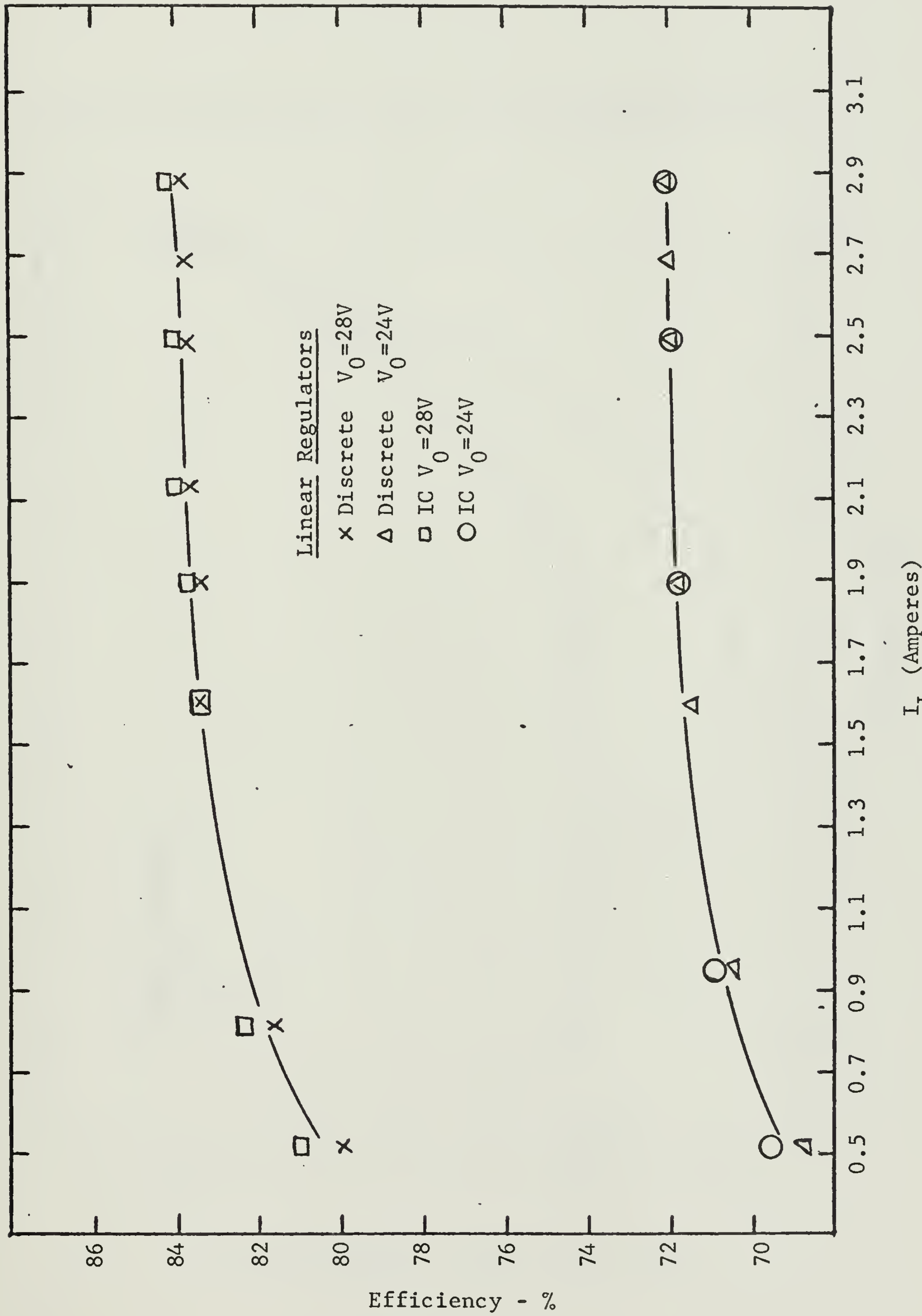

Discrete Regulator
$V_0$ = 28V
O $I_L$ = 2.14A
X $I_L$ = 1.6A
· $I_L$ = 0.8A
$V_{IN}$ (Volts)
27
28
29
30
31
32
33
34
35
36
37
38
39
40
Line Regulation - % $V_0$
0.1
0
-0.1
-0.2
-0.3


0.1
0
-0.1
-0.2
-0.3
Line Regulation - % V0
27
28
29
30
31
32
33
34
35
36
37
38
39
40
Discrete Regulator
V0 = 24V
O IL = 2.5A
X IL = 1.9A
• IL = 0.94A

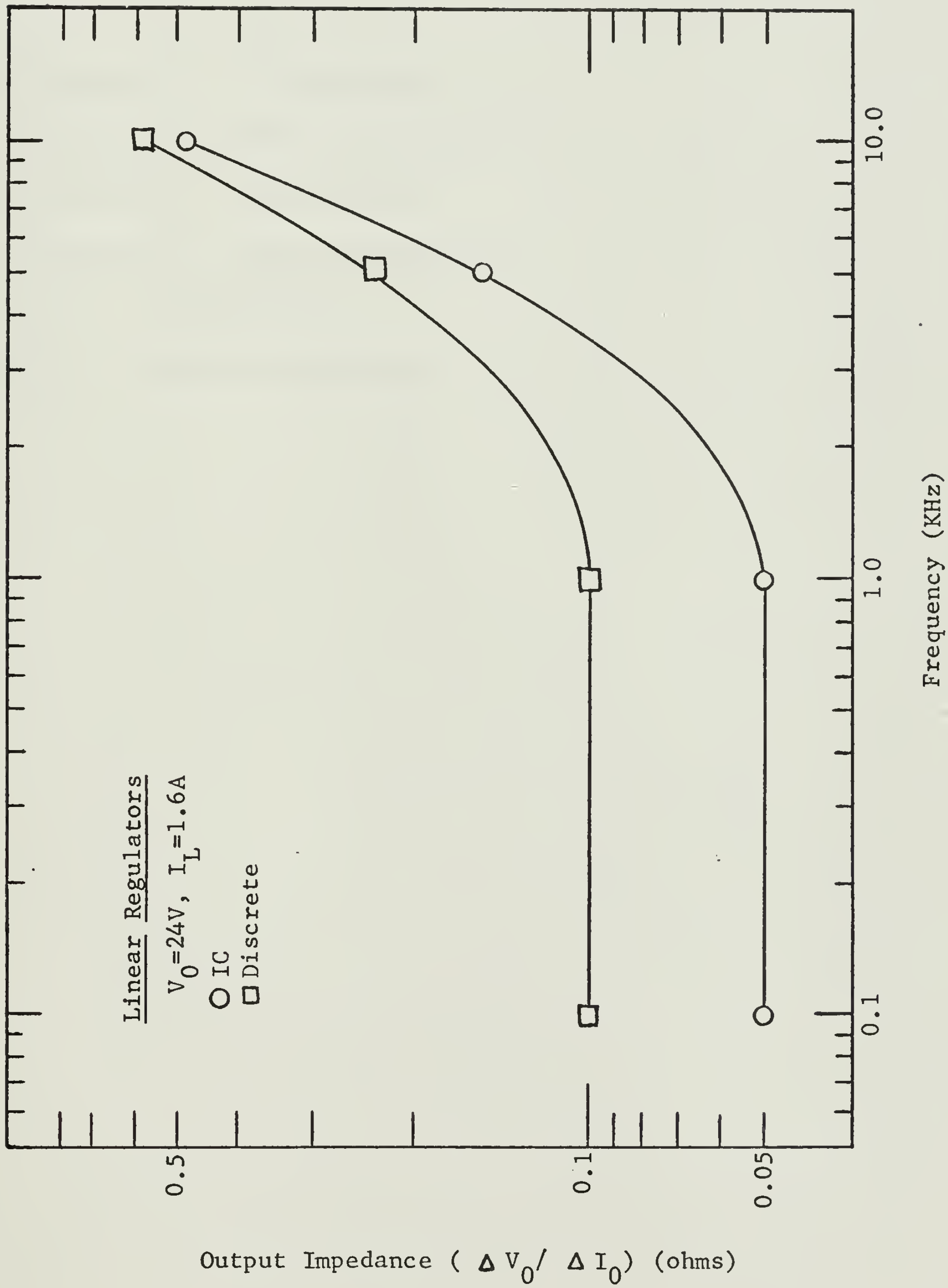


V_IN = 33V
Discrete
O V_0=24V
X V_0=28V
IC
□ V_0=24V
Δ V_0=28V
0.3
0.2
0.1
0
-0.1
Load Regulation - % V_0
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
I_L (Amperes)


V_IN = 33V
• Discrete, T_A=27°C
⊙ Discrete, T_A=63°C
X IC , T_A=27°C
⊗ IC , T_A=63°C
I_L (Amperes)
V_0 (Volts)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
24.5
24.4
24.3
24.2
24.1
24.0
23.9
23.8
23.7

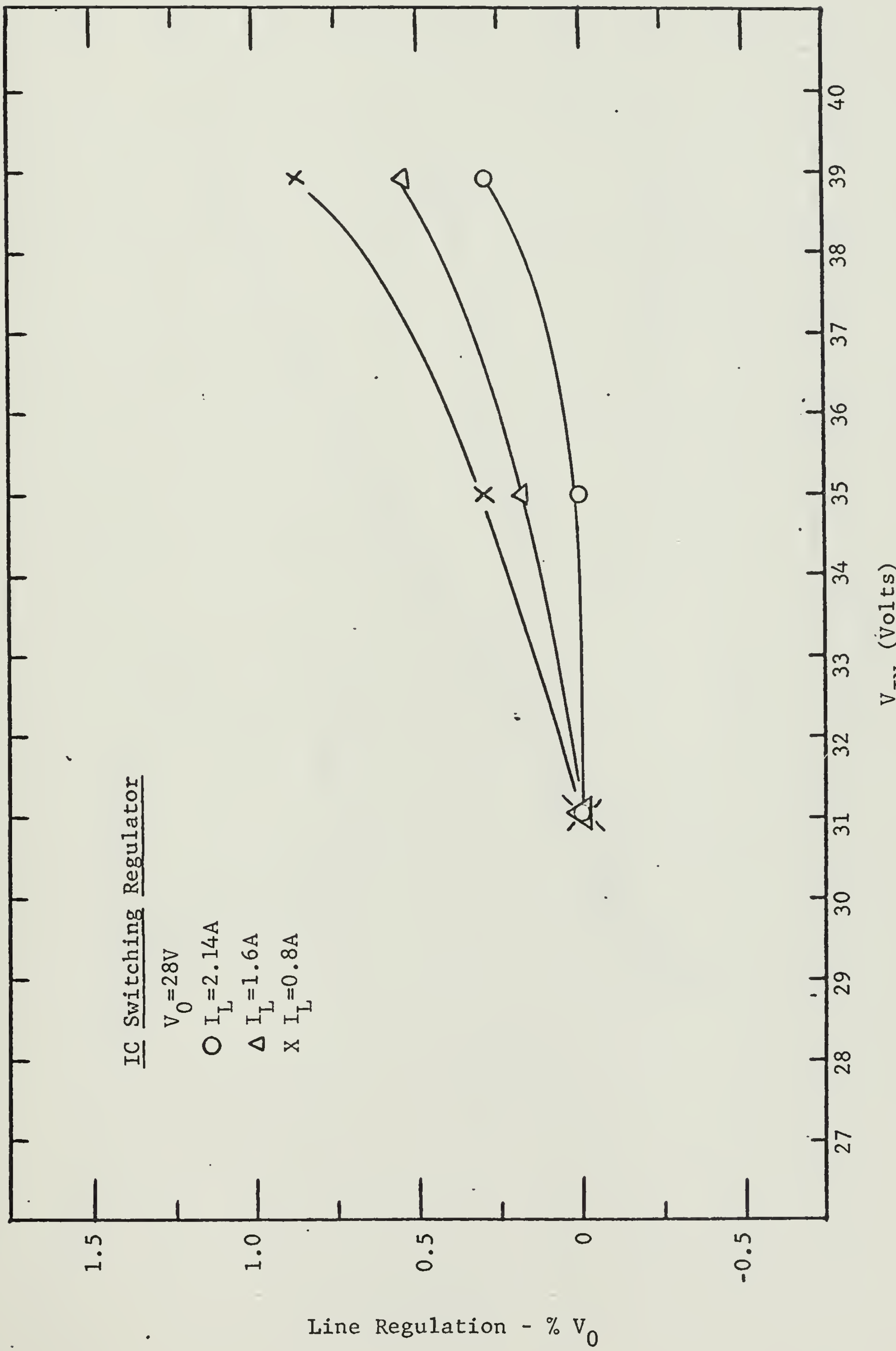


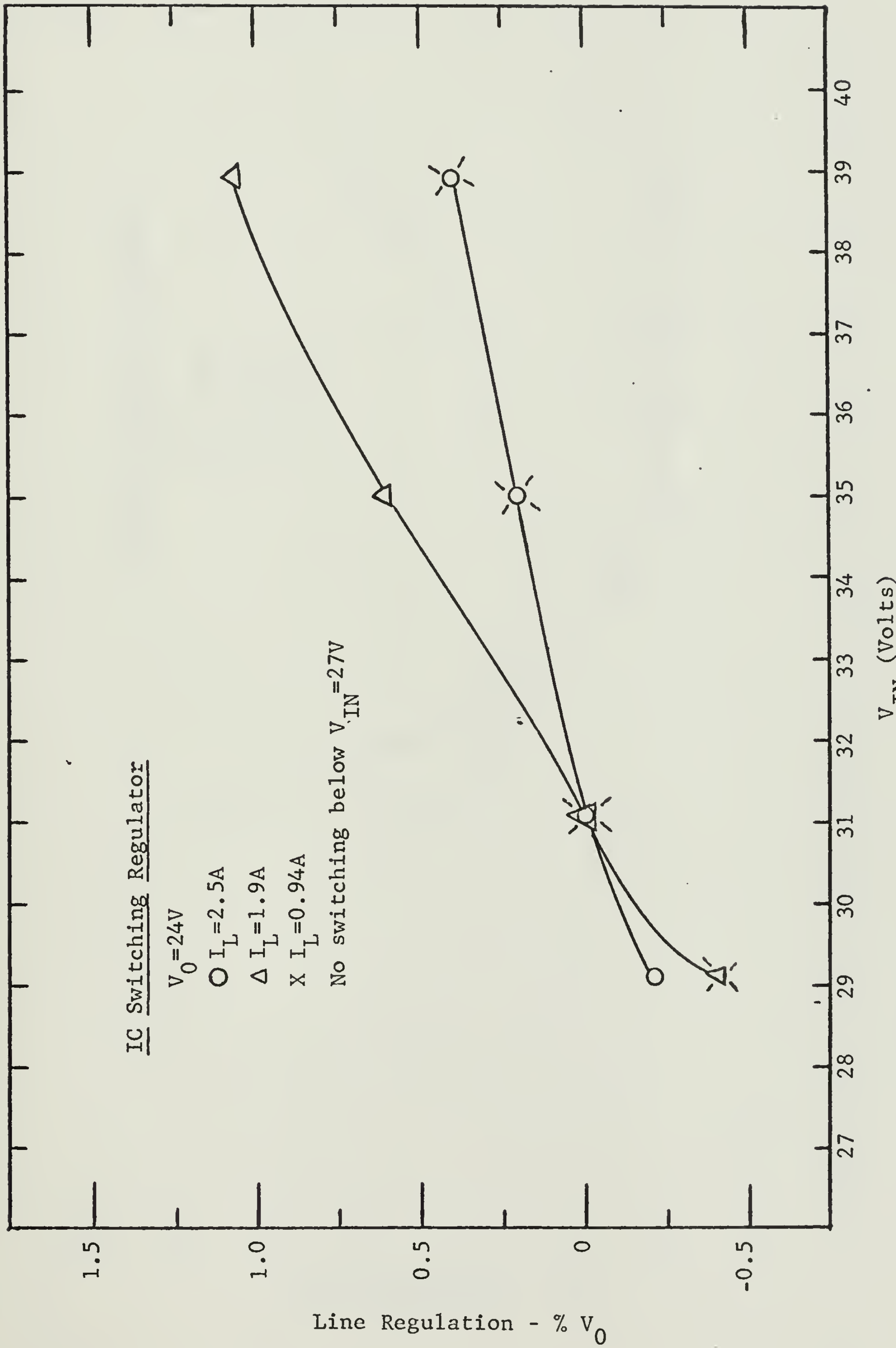
Linear Regulators
× Discrete $V_0$=28V
Δ Discrete $V_0$=24V
□ IC $V_0$=28V
○ IC $V_0$=24V
Efficiency - %
86
84
82
80
78
76
74
72
70
$I_L$ (Amperes)
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1

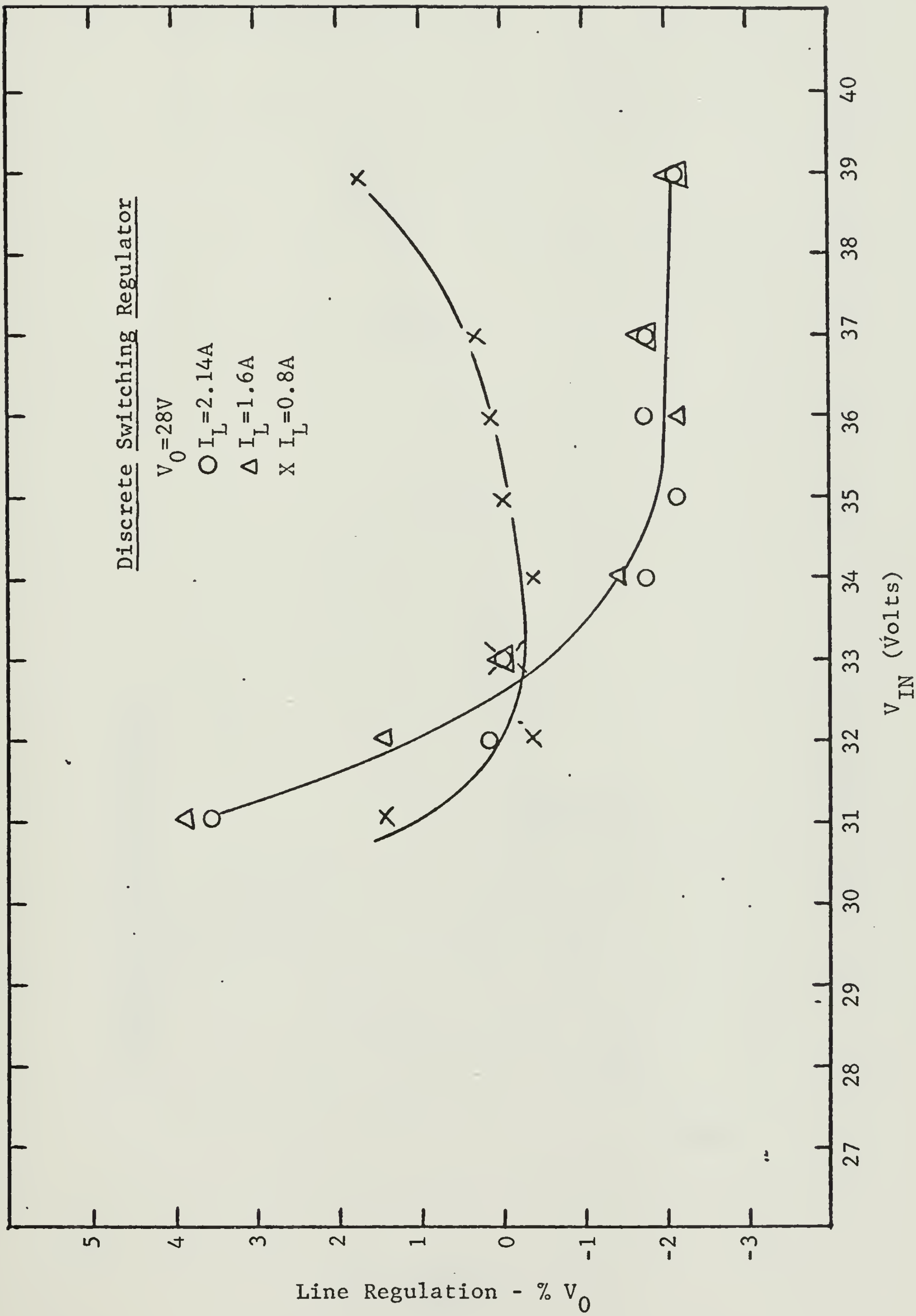

Linear Regulators
$V_0$=24V, $I_L$=1.6A
IC
Discrete
0.1
1.0
10.0
Frequency (KHz)
0.5
0.1
0.05
Output Impedance ( $\Delta V_0 / \Delta I_0$) (ohms)

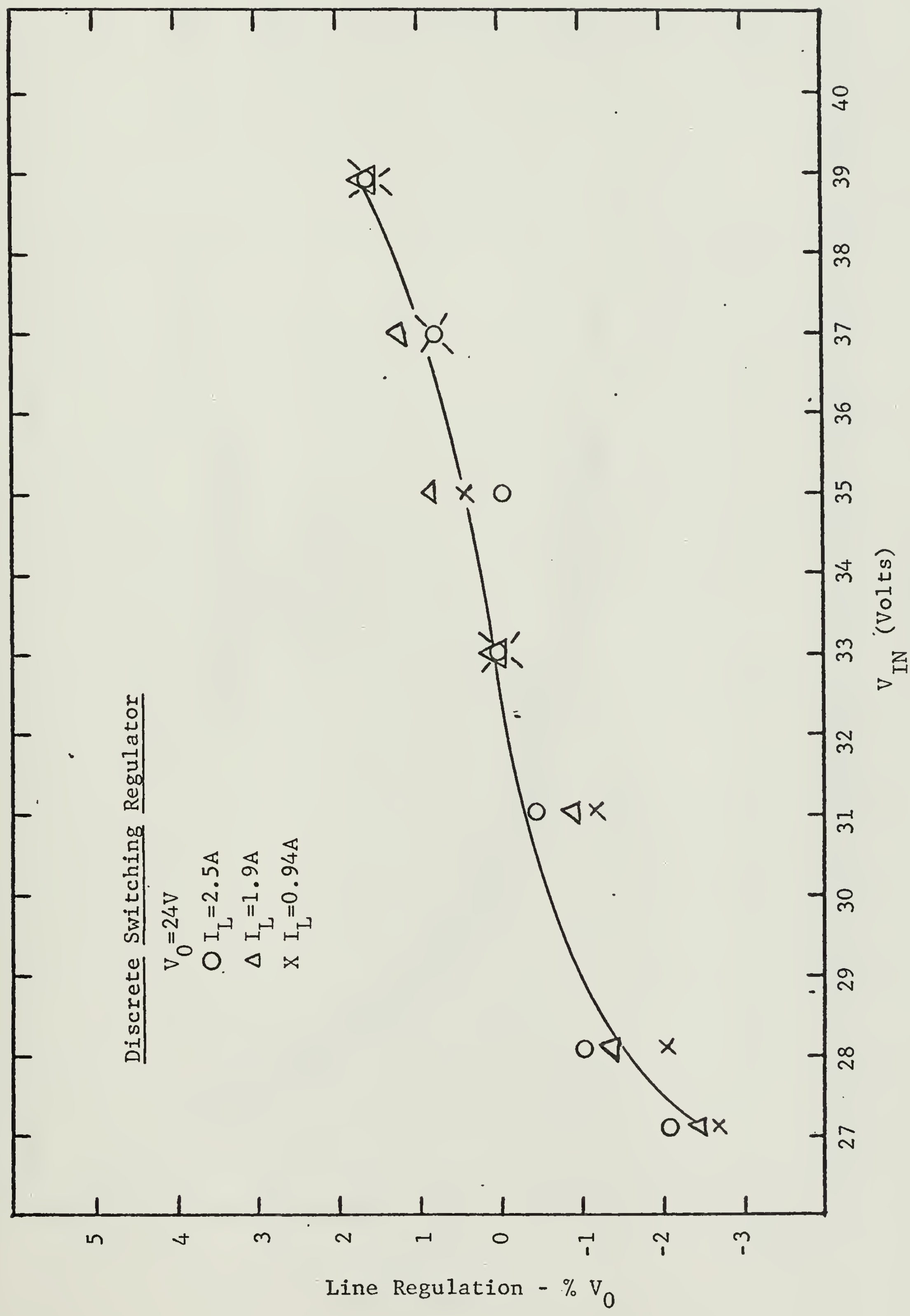
## APPENDIX B

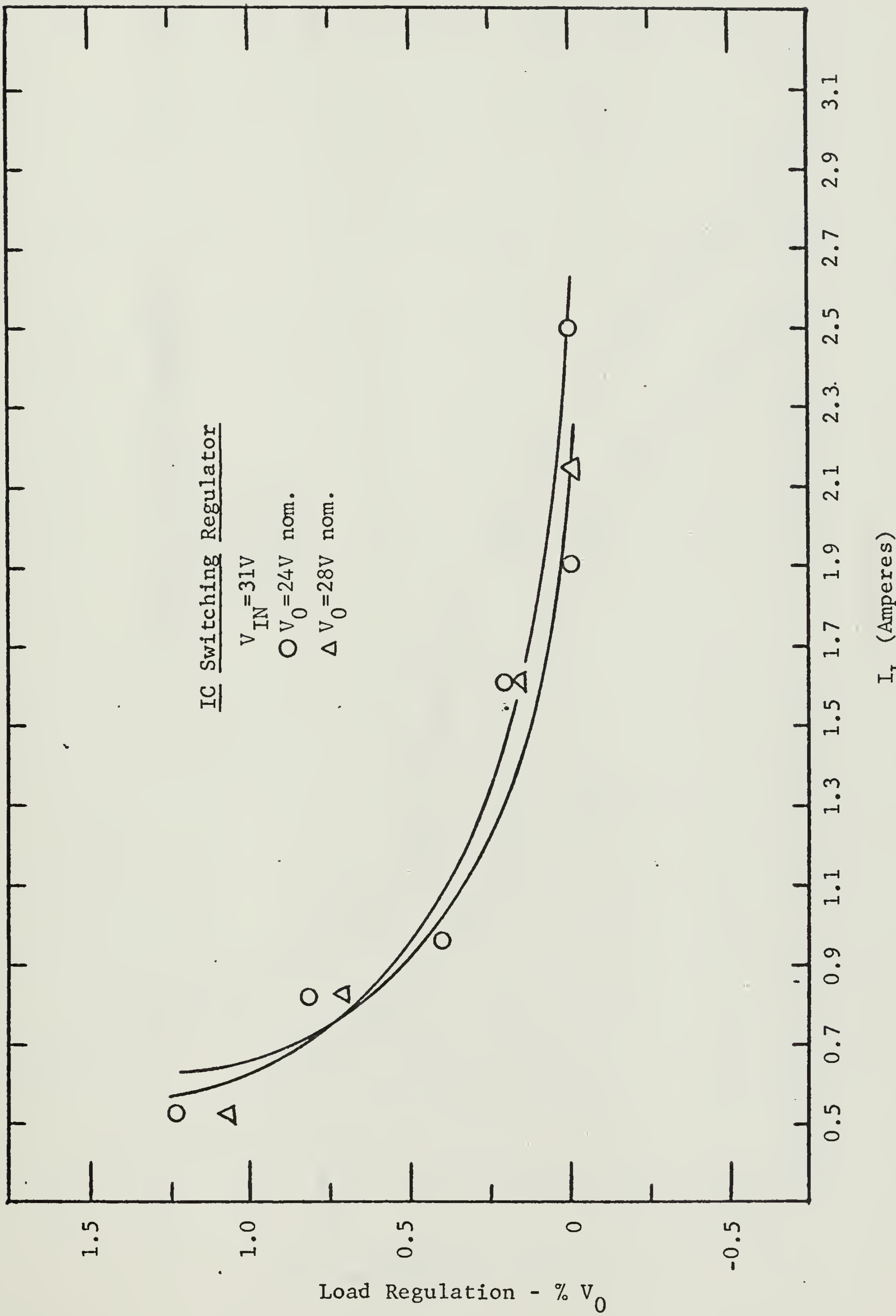
Characteristic Curves of Switching Regulators

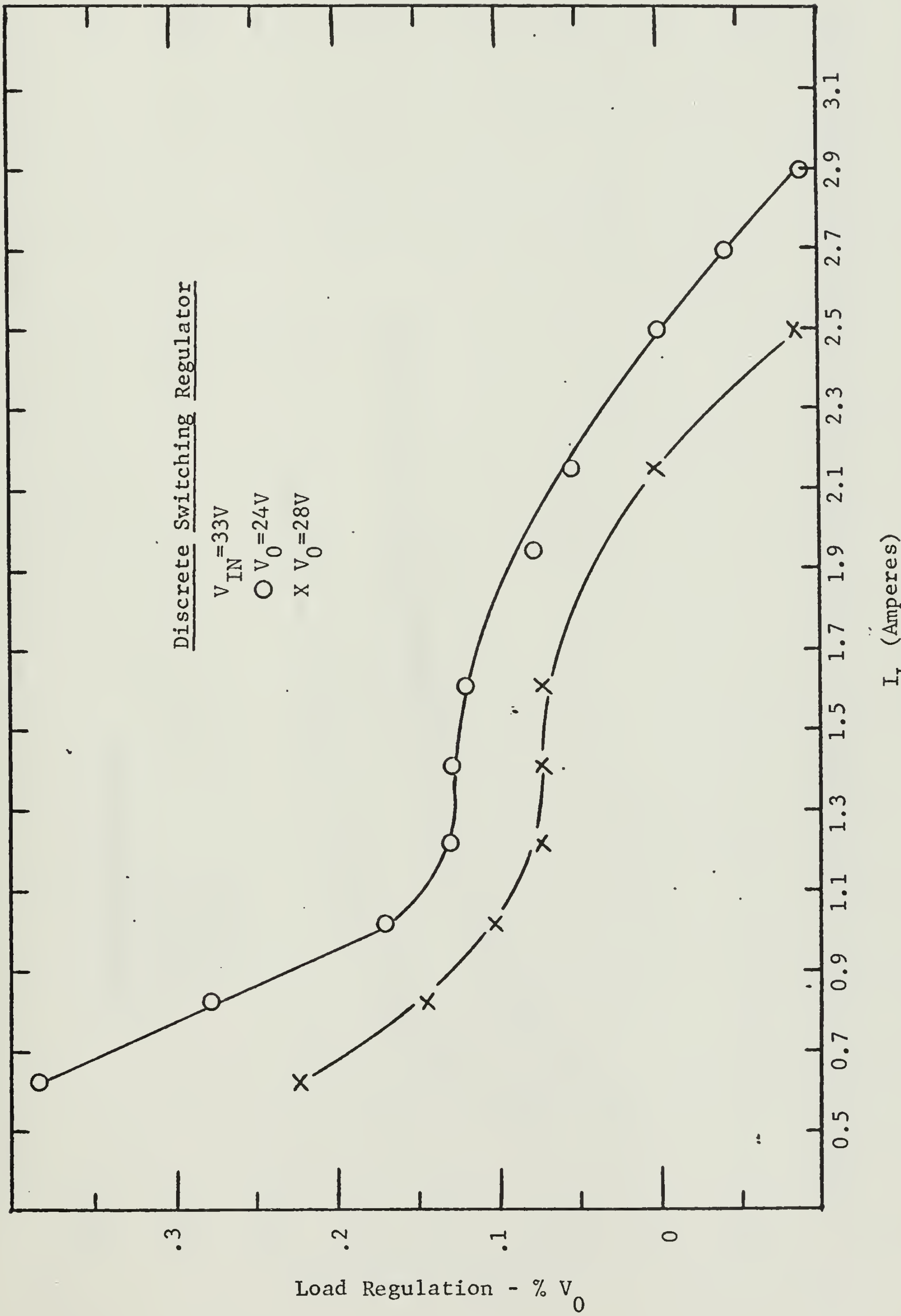

IC Switching Regulator
V0=28V
O IL=2.14A
Δ IL=1.6A
X IL=0.8A
27 28 29 30 31 32 33 34 35 36 37 38 39 40
VIN (Volts)
1.5 1.0 0.5 0 -0.5
Line Regulation - % V0


IC Switching Regulator
$V_0$=24V
O $I_L$=2.5A
Δ $I_L$=1.9A
X $I_L$=0.94A
No switching below $V_{IN}$=27V
$V_{IN}$ (Volts)
27
28
29
30
31
32
33
34
35
36
37
38
39
40
Line Regulation - % $V_0$
1.5
1.0
0.5
0
-0.5

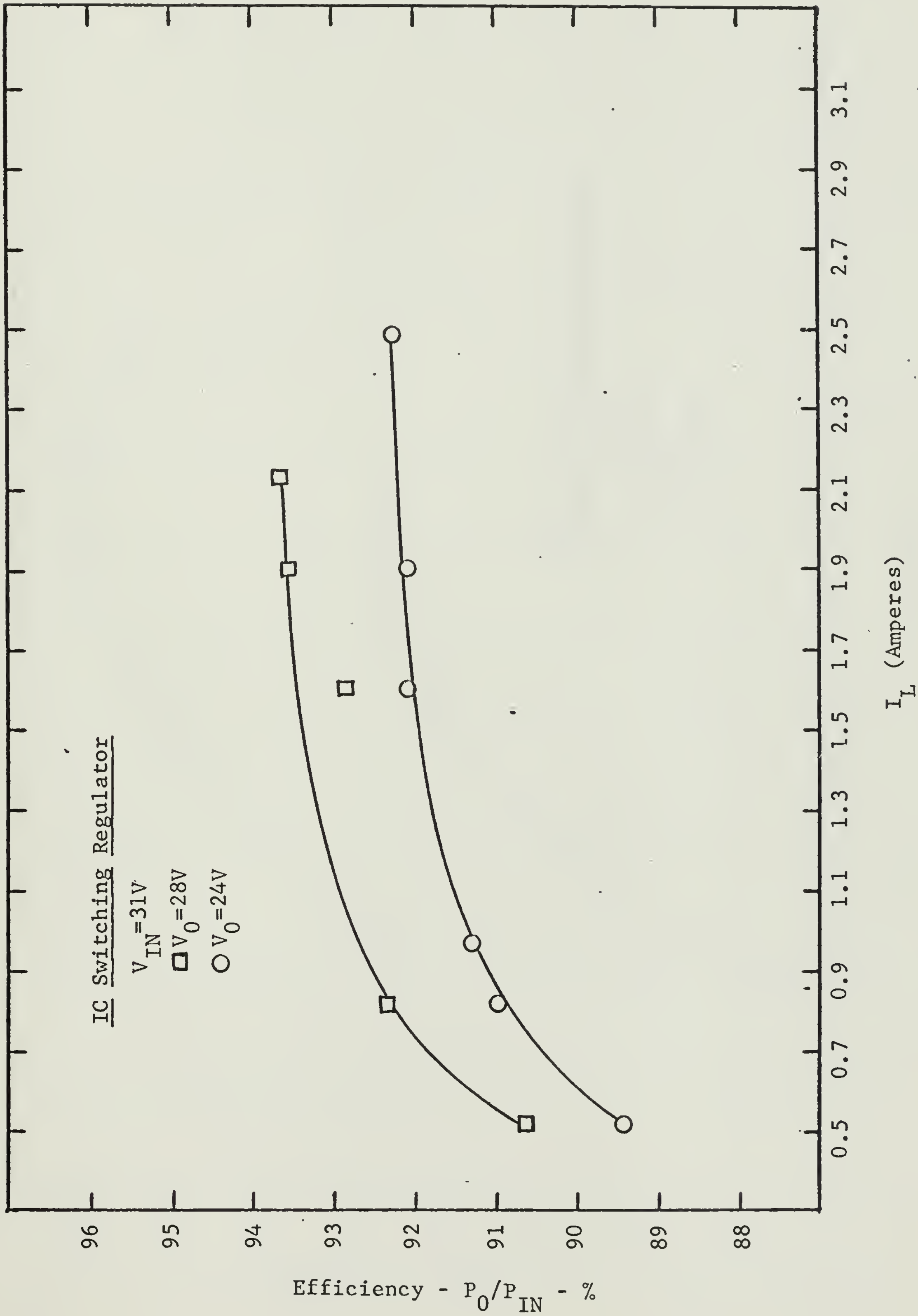

Discrete Switching Regulator
V0=28V
O IL=2.14A
Δ IL=1.6A
X IL=0.8A
Line Regulation - % V0
VIN (Volts)
5
4
3
2
1
0
-1
-2
-3
27
28
29
30
31
32
33
34
35
36
37
38
39
40

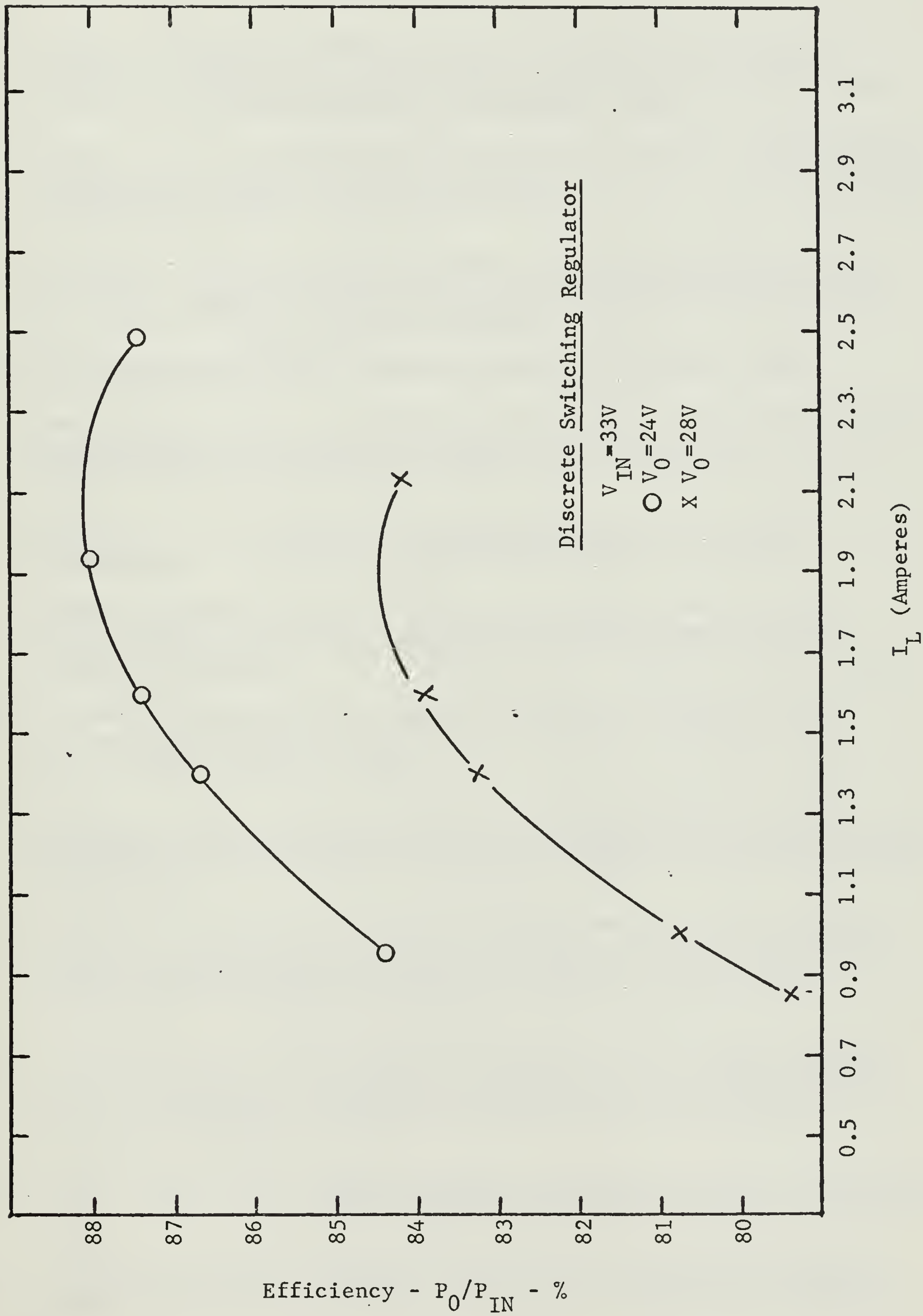

Discrete Switching Regulator
V0=24V
O IL=2.5A
Δ IL=1.9A
X IL=0.94A
Line Regulation - % V0
VIN (Volts)
27
28
29
30
31
32
33
34
35
36
37
38
39
40
5
4
3
2
1
0
-1
-2
-3


IC Switching Regulator
$V_{IN}$=31V
○ $V_0$=24V nom.
Δ $V_0$=28V nom.
$I_L$ (Amperes)
Load Regulation - % $V_0$
1.5
1.0
0.5
0
-0.5
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1



Discrete Switching Regulator
V_IN=33V
O V_0=24V
X V_0=28V
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
I_L (Amperes)
.3
.2
.1
0
Load Regulation - % V_0


IC Switching Regulator
$V_{IN}$=31V
$V_0$=28V
$V_0$=24V
96
95
94
93
92
91
90
89
88
Efficiency - $P_0/P_{IN}$ - %
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3
2.5
2.7
2.9
3.1
$I_L$ (Amperes)


Discrete Switching Regulator
V_IN=33V
O V_0=24V
X V_0=28V
I_L (Amperes)
Efficiency - P_0/P_IN - %
88
87
86
85
84
83
82
81
80
0.5
0.7
0.9
1.1
1.3
1.5
1.7
1.9
2.1
2.3.
2.5
2.7
2.9
3.1

## BIBLIOGRAPHY


1. Angello, Joseph P., "Static, Silent, Thermoelectric Power Sources," Proceedings 23rd Annual Power Sources Conference, p. 165-168: PSC Publications Committee, 1969.

2. Evans, G. E., "Hydrazine-Air Fuel Cell Controls," Proceedings 22nd Annual Power Sources Conference, p. 1-5, PSC Publications Committee, 1968.

3. Frysinger, G. R., "High Reliability (10,000 HR MTBF) Power Sources," Proceedings 23rd Annual Power Sources Conference, p. 17-18, PSC Publications Committee, 1969.

4. GE Transistor Manual, General Electric Company, 1964.

5. Malaspina, F. P., "30 Watt Metal Hydride-Air Fuel Cell System," Proceedings 22nd Annual Power Sources Conference, p. 20-21, PSC Publications Committee, 1968.

6. Millman, J. and Taub, H., Pulse, Digital, and Switching Waveforms, p. 362-403, McGraw-Hill, 1965.

7. Motorola Semiconductor Products Application Note AN-163, Silicon Power Transistors Provide New Solutions to Voltage Control Problems, by J. Takesuye and H. Weber, October, 1968.

8. Motorola Semiconductor Products Application Note AN-181, A Regulated Power Supply Using a Reference Amplifier, by H. F. Weber, March, 1969.

9. Motorola Semiconductor Products Application Note AN-457, Switching Voltage Regulator Uses Discrete and Integrated-Circuit Approaches, by B. Shiver, February, 1969.

10. National Aeronautics and Space Administration Technical Note D-5586, Design Analysis and Performance of a 2.5 kVA Pulse-Width-Modulated Static Inverter, by Francis Gourash and Arthur G. Birchenough, February, 1970.

11. National Aeronautics and Space Administration Technical Note D-5643, Design and Performance Analysis of a Medium-Power DC-DC Converter, by Arthur G. Birchenough and Francis Gourash, February, 1970.

12. Petty, John Allen, Characteristics and Design of Power Converters, Masters Thesis, Naval Postgraduate School, Monterey, 1967.

13. "Precision Voltage Regulator, $\mu$A723C," Fairchild Linear Integrated Circuits, p. 694-699, Fairchild Semiconductor, 1968.

14. RCA Silicon Power Circuits Manual, Radio Corporation of America, 1969.

15. RCA Transistor Thyristor and Diode Manual, Radio Corporation of America, 1969.

16. Reich, H. J., Skalnik, J. G., and Krauss, H. L., Theory and Applications of Active Devices, p. 380-404, Van Nostrand, 1966.

17. Terman, F. E., Electronic and Radio Engineering, p. 360-363, 702-730, McGraw-Hill, 1955.

18. Thesis Booklet 1970, p. 72-73, Naval Postgraduate School, 1970.

19. Weideman, E. A., Engineering Application and Current Capabilities of Secondary Batteries and Fuel Cells (AD855955), General Dynamics, Convair Division, January, 1968.

## INITIAL DISTRIBUTION LIST

| | | No. Copies |
|---|---|---|
| 1. | Defense Documentation Center<br>Cameron Station<br>Alexandria, Virginia 22314 | 2 |
| 2. | Library, Code 0212<br>Naval Postgraduate School<br>Monterey, California 93940 | 2 |
| 3. | Commandant of the Marine Corps (Code A04C)<br>Headquarters, U. S. Marine Corps<br>Washington, D. C. 20380 | 1 |
| 4. | Professor W. M. Bauer<br>Department of Electrical Engineering<br>Naval Postgraduate School<br>Monterey, California 93940 | 1 |
| 5. | Professor R. P. Murray<br>Department of Electrical Engineering<br>Naval Postgraduate School<br>Monterey, California 93940 | 1 |
| 6. | Major Thomas J. Solak, USMC<br>Marine Aviation Detachment<br>Naval Missile Center<br>Point Mugu, California 93041 | 1 |

UNCLASSIFIED

Security Classification

# DOCUMENT CONTROL DATA - R & D

*(Security classification of title, body of abstract and indexing annotation must be entered when the overall report is classified)*

| | |
|---|---|
| 1. ORIGINATING ACTIVITY (Corporate author) Naval Postgraduate School, Monterey, California 93940 | 2a. REPORT SECURITY CLASSIFICATION Unclassified |
| | 2b. GROUP |

3. REPORT TITLE

Study of Transistor Linear and Switching Voltage Regulators for Use in Power Conditioning

4. DESCRIPTIVE NOTES (Type of report and, inclusive dates)

Master's Thesis; December 1970

5. AUTHOR(S) (First name, middle initial, last name)

Thomas Joseph Solak

| 6. REPORT DATE | 7a. TOTAL NO. OF PAGES | 7b. NO. OF REFS |
|---|---|---|
| December 1970 | 63 | 19 |

| | |
|---|---|
| 8a. CONTRACT OR GRANT NO. | 9a. ORIGINATOR'S REPORT NUMBER(S) |
| b. PROJECT NO. | |
| c. | 9b. OTHER REPORT NO(S) (Any other numbers that may be assigned this report) |
| d. | |

10. DISTRIBUTION STATEMENT

This document has been approved for public release and sale; its distribution is unlimited.

| 11. SUPPLEMENTARY NOTES | 12. SPONSORING MILITARY ACTIVITY |
|---|---|
| | Naval Postgraduate School, Monterey, California 93940 |

13. ABSTRACT

A requirement exists for a portable direct energy source 60 watt power supply with adjustable output voltage between 24 and 28 volts. Integrated circuit and discrete transistor linear and switching voltage regulators with these outputs were designed, breadboarded and tested with intent toward use in such power supplies. A summary of design characteristics of the transistors and circuits is given, while the resulting test data is presented in tabular and graphical form. A feasibility study of using the tested regulators in conjunction with a dc-dc converter to form a power conditioner is also presented.

| 14. KEY WORDS | LINK A | | LINK B | | LINK C | |
|---|---|---|---|---|---|---|
| | ROLE | WT | ROLE | WT | ROLE | WT |
| DC to DC converter | | | | | | |
| Direct energy conversion | | | | | | |
| Limiter circuits | | | | | | |
| Power supply circuits | | | | | | |
| Switching circuits | | | | | | |
| Voltage regulation | | | | | | |
| Voltage regulators | | | | | | |

Thesis 125690
S66394 Solak
c.1 Study of transistor linear and switching voltage regulators for use in power conditioning.